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(54) **PLETHYSMOGRAPHIC RESPIRATION RATE DETECTION**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

3,682,161 A 8/1972 Alibert
4,109,643 A 8/1978 Bond et al.
(Continued)

FOREIGN PATENT DOCUMENTS

CA 2262236 4/2008
EP 0716628 12/1998
(Continued)

OTHER PUBLICATIONS

US 8,845,543 B2, 09/2014, Diab et al. (withdrawn)
(Continued)

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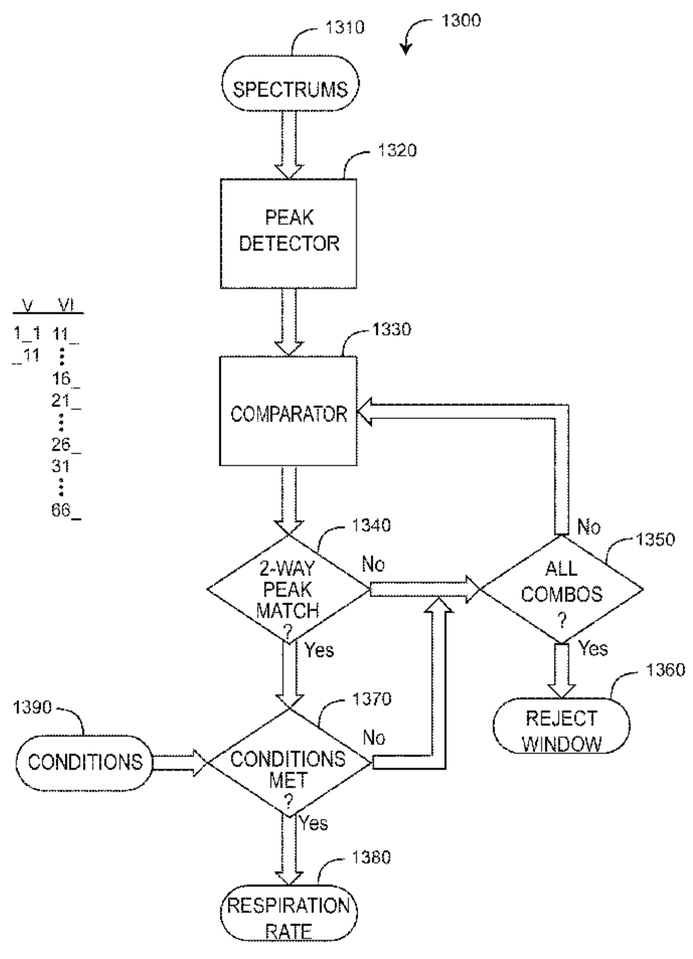
(57) **ABSTRACT**

A plethysmographic respiration processor is responsive to respiratory effects appearing on a blood volume waveform and the corresponding detected intensity waveform measured with an optical sensor at a blood perfused peripheral tissue site so as to provide a measurement of respiration rate. A preprocessor identifies a windowed pleth corresponding to a physiologically acceptable series of plethysmograph waveform pulses. Multiple processors derive different parameters responsive to particular respiratory effects on the windowed pleth. Decision logic determines a respiration rate based upon at least a portion of these parameters.

16 Claims, 17 Drawing Sheets



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(56) **References Cited**

U.S. PATENT DOCUMENTS

4,127,749	A	11/1978	Atoji et al.
4,326,143	A	4/1982	Guth et al.
4,507,653	A	3/1985	Bayer
4,537,200	A	8/1985	Widrow
4,685,140	A	8/1987	Mount, II
4,714,341	A	12/1987	Hamaguri
4,848,901	A	7/1989	Hood, Jr.
4,867,165	A	9/1989	Noller et al.
4,884,809	A	12/1989	Rowan
4,958,638	A	9/1990	Sharpe et al.
4,960,128	A	10/1990	Gordon et al.
4,964,408	A	10/1990	Hink et al.
5,033,032	A	7/1991	Houghtaling
5,041,187	A	8/1991	Hink et al.
5,069,213	A	12/1991	Polczynski
5,111,817	A	5/1992	Clark et al.
5,119,814	A	6/1992	Minnich
5,143,078	A	9/1992	Mather et al.
5,163,438	A	11/1992	Gordon et al.
5,273,036	A	12/1993	Kronberg et al.
5,277,181	A	1/1994	Mendelson et al.
5,309,922	A	5/1994	Schechter et al.
5,319,355	A	6/1994	Russek
5,337,744	A	8/1994	Branigan
5,341,805	A	8/1994	Stavridi et al.
5,353,798	A	10/1994	Sieben
D353,195	S	12/1994	Savage et al.
D353,196	S	12/1994	Savage et al.
5,377,302	A	12/1994	Tsiang
5,377,676	A	1/1995	Vari et al.
D359,546	S	6/1995	Savage et al.
5,431,170	A	7/1995	Mathews
5,436,499	A	7/1995	Namavar et al.
D361,840	S	8/1995	Savage et al.
D362,063	S	9/1995	Savage et al.
5,448,996	A	9/1995	Bellin et al.
5,452,717	A	9/1995	Branigan et al.
D363,120	S	10/1995	Savage et al.
5,456,252	A	10/1995	Vari et al.
5,479,934	A	1/1996	Imran
5,482,036	A	1/1996	Diab et al.
5,490,505	A	2/1996	Diab et al.
5,494,043	A	2/1996	O'Sullivan et al.
5,533,511	A	7/1996	Kaspari et al.
5,534,851	A	7/1996	Russek
5,553,615	A	9/1996	Carim et al.
5,561,275	A	10/1996	Savage et al.
5,562,002	A	10/1996	Lalin
5,590,649	A	1/1997	Caro et al.
5,602,924	A	2/1997	Durand et al.
5,613,496	A	3/1997	Arand et al.
5,632,272	A	5/1997	Diab et al.
5,638,403	A	6/1997	Birchler et al.
5,638,816	A	6/1997	Kiani-Azarbayjany et al.
5,638,818	A	6/1997	Diab et al.
5,645,440	A	7/1997	Tobler et al.
5,671,191	A	9/1997	Gerdt
5,671,914	A	9/1997	Kalkhoran et al.
5,685,299	A	11/1997	Diab et al.
5,724,983	A	3/1998	Selker et al.
5,726,440	A	3/1998	Kalkhoran et al.
D393,830	S	4/1998	Tobler et al.
5,743,262	A	4/1998	Lepper, Jr. et al.
5,747,806	A	5/1998	Khalil et al.
5,750,994	A	5/1998	Schlager
5,758,644	A	6/1998	Diab et al.
5,760,910	A	6/1998	Lepper, Jr. et al.
5,766,127	A	6/1998	Pologe et al.
5,769,785	A	6/1998	Diab et al.
5,782,757	A	7/1998	Diab et al.
5,785,659	A	7/1998	Caro et al.
5,791,347	A	8/1998	Flaherty et al.
5,810,734	A	9/1998	Caro et al.
5,819,007	A	10/1998	Elghazzawi
5,823,950	A	10/1998	Diab et al.
5,830,131	A	11/1998	Caro et al.
5,833,618	A	11/1998	Caro et al.
5,860,919	A	1/1999	Kiani-Azarbayjany et al.
5,862,805	A	1/1999	Nitzan
5,865,736	A	2/1999	Baker, Jr. et al.
5,890,929	A	4/1999	Mills et al.
5,904,654	A	5/1999	Wohltmann et al.
5,919,134	A	7/1999	Diab
5,928,156	A	7/1999	Krumbiegel
5,934,925	A	8/1999	Tobler et al.
5,940,182	A	8/1999	Lepper, Jr. et al.
5,984,893	A	11/1999	Ward
5,987,343	A	11/1999	Kinast
5,995,855	A	11/1999	Kiani et al.
5,997,343	A	12/1999	Mills et al.
6,002,952	A	12/1999	Diab et al.
6,010,937	A	1/2000	Karam et al.
6,011,986	A	1/2000	Diab et al.
6,027,452	A	2/2000	Flaherty et al.
6,029,665	A	2/2000	Berthon-Jones
6,036,642	A	3/2000	Diab et al.
6,040,578	A	3/2000	Malin et al.
6,045,509	A	4/2000	Caro et al.
6,064,910	A	5/2000	Andersson et al.
6,066,204	A	5/2000	Haven
6,067,462	A	5/2000	Diab et al.
6,081,735	A	6/2000	Diab et al.
6,083,172	A	7/2000	Baker et al.
6,088,607	A	7/2000	Diab et al.
6,091,973	A	7/2000	Colla et al.
6,110,522	A	8/2000	Lepper, Jr. et al.
6,112,171	A	8/2000	Sugiyama et al.
6,115,673	A	9/2000	Malin et al.
6,124,597	A	9/2000	Shehada
6,128,521	A	10/2000	Marro et al.
6,129,675	A	10/2000	Jay
6,138,675	A	10/2000	Berthon-Jones
6,139,505	A	10/2000	Murphy
6,144,868	A	11/2000	Parker

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,151,516	A	11/2000	Kiani-Azarbayjany et al.
6,152,754	A	11/2000	Gerhardt et al.
6,157,850	A	12/2000	Diab et al.
6,165,005	A	12/2000	Mills et al.
6,165,151	A	12/2000	Weiner
6,168,568	B1	1/2001	Gavriely
6,178,343	B1	1/2001	Bindszus et al.
6,184,521	B1	2/2001	Coffin, IV et al.
6,206,830	B1	3/2001	Diab et al.
6,229,856	B1	5/2001	Diab et al.
6,232,609	B1	5/2001	Snyder et al.
6,236,872	B1	5/2001	Diab et al.
6,241,683	B1	6/2001	Macklem et al.
6,248,083	B1	6/2001	Smith et al.
6,253,097	B1	6/2001	Aronow et al.
6,254,551	B1	7/2001	Varis
6,255,708	B1	7/2001	Sudharsanan et al.
6,256,523	B1	7/2001	Diab et al.
6,261,238	B1	7/2001	Gavriely
6,263,222	B1	7/2001	Diab et al.
6,278,522	B1	8/2001	Lepper, Jr. et al.
6,280,213	B1	8/2001	Tobler et al.
6,280,381	B1	8/2001	Malin et al.
6,285,896	B1	9/2001	Tobler et al.
6,301,493	B1	10/2001	Marro et al.
6,308,089	B1	10/2001	von der Ruhr et al.
6,317,627	B1	11/2001	Ennen et al.
6,321,100	B1	11/2001	Parker
6,325,761	B1	12/2001	Jay
6,331,162	B1	12/2001	Mitchell
6,334,065	B1	12/2001	Al-Ali et al.
6,343,224	B1	1/2002	Parker
6,349,228	B1	2/2002	Kiani et al.
6,360,114	B1	3/2002	Diab et al.
6,361,501	B1	3/2002	Amano et al.
6,368,283	B1	4/2002	Xu et al.
6,371,921	B1	4/2002	Caro et al.
6,377,829	B1	4/2002	Al-Ali
6,383,143	B1	5/2002	Rost
6,385,471	B1	5/2002	Mortz
6,388,240	B2	5/2002	Schulz et al.
6,397,091	B2	5/2002	Diab et al.
6,411,373	B1	6/2002	Garside et al.
6,415,167	B1	7/2002	Blank et al.
6,430,437	B1	8/2002	Marro
6,430,525	B1	8/2002	Weber et al.
6,443,907	B1	9/2002	Mansy et al.
6,463,311	B1	10/2002	Diab
6,470,199	B1	10/2002	Kopotic et al.
6,486,588	B2	11/2002	Doron et al.
6,487,429	B2	11/2002	Hockersmith et al.
6,491,647	B1	12/2002	Bridger et al.
6,501,975	B2	12/2002	Diab et al.
6,505,059	B1	1/2003	Kollias et al.
6,515,273	B2	2/2003	Al-Ali
6,517,497	B2	2/2003	Rymut et al.
6,519,487	B1	2/2003	Parker
6,525,386	B1	2/2003	Mills et al.
6,526,300	B1	2/2003	Kiani et al.
6,534,012	B1	3/2003	Hazen et al.
6,541,756	B2	4/2003	Schulz et al.
6,542,764	B1	4/2003	Al-Ali et al.
6,580,086	B1	6/2003	Schulz et al.
6,584,336	B1	6/2003	Ali et al.
6,587,196	B1	7/2003	Stippick et al.
6,587,199	B1	7/2003	Luu
6,595,316	B2	7/2003	Cybulski et al.
6,597,932	B2	7/2003	Tian et al.
6,597,933	B2	7/2003	Kiani et al.
6,606,511	B1	8/2003	Ali et al.
6,632,181	B2	10/2003	Flaherty et al.
6,635,559	B2	10/2003	Greenwald et al.
6,639,668	B1	10/2003	Trepagnier
6,640,116	B2	10/2003	Diab
6,640,117	B2	10/2003	Makarewicz et al.
6,643,530	B2	11/2003	Diab et al.
6,647,280	B2	11/2003	Bahr et al.
6,650,917	B2	11/2003	Diab et al.
6,654,624	B2	11/2003	Diab et al.
6,658,276	B2	12/2003	Kiani et al.
6,659,960	B2	12/2003	Derksen et al.
6,661,161	B1	12/2003	Lanzo et al.
6,671,531	B2	12/2003	Al-Ali et al.
6,678,543	B2	1/2004	Diab et al.
6,684,090	B2	1/2004	Ali et al.
6,684,091	B2	1/2004	Parker
6,697,656	B1	2/2004	Al-Ali
6,697,657	B1	2/2004	Shehada et al.
6,697,658	B2	2/2004	Al-Ali
RE38,476	E	3/2004	Diab et al.
6,699,194	B1	3/2004	Diab et al.
6,709,402	B2	3/2004	Dekker
6,714,804	B2	3/2004	Al-Ali et al.
RE38,492	E	4/2004	Diab et al.
6,721,582	B2	4/2004	Trepagnier et al.
6,721,585	B1	4/2004	Parker
6,725,074	B1	4/2004	Kastle
6,725,075	B2	4/2004	Al-Ali
6,728,560	B2	4/2004	Kollias et al.
6,735,459	B2	5/2004	Parker
6,738,652	B2	5/2004	Mattu et al.
6,745,060	B2	6/2004	Diab et al.
6,754,516	B2	6/2004	Mannheimer
6,760,607	B2	7/2004	Al-Ali
6,766,038	B1	7/2004	Sakuma et al.
6,770,028	B1	8/2004	Ali et al.
6,771,994	B2	8/2004	Kiani et al.
6,788,965	B2	9/2004	Ruchti et al.
6,792,300	B1	9/2004	Diab et al.
6,813,511	B2	11/2004	Diab et al.
6,816,241	B2	11/2004	Grubisic
6,816,741	B2	11/2004	Diab
6,822,564	B2	11/2004	Al-Ali
6,826,419	B2	11/2004	Diab et al.
6,830,711	B2	12/2004	Mills et al.
6,839,581	B1	1/2005	El-Solh et al.
6,850,787	B2	2/2005	Weber et al.
6,850,788	B2	2/2005	Al-Ali
6,852,083	B2	2/2005	Caro et al.
6,861,639	B2	3/2005	Al-Ali
6,869,402	B2	3/2005	Arnold
6,876,931	B2	4/2005	Lorenz et al.
6,898,452	B2	5/2005	Al-Ali et al.
6,920,345	B2	7/2005	Al-Ali et al.
6,931,268	B1	8/2005	Kiani-Azarbayjany et al.
6,934,570	B2	8/2005	Kiani et al.
6,939,305	B2	9/2005	Flaherty et al.
6,943,348	B1	9/2005	Coffin IV
6,950,687	B2	9/2005	Al-Ali
6,956,649	B2	10/2005	Acosta et al.
6,961,598	B2	11/2005	Diab
6,970,792	B1	11/2005	Diab
6,979,812	B2	12/2005	Al-Ali
6,985,764	B2	1/2006	Mason et al.
6,990,364	B2	1/2006	Ruchti et al.
6,993,371	B2	1/2006	Kiani et al.
6,996,427	B2	2/2006	Ali et al.
6,998,247	B2	2/2006	Monfre et al.
6,999,904	B2	2/2006	Weber et al.
7,003,338	B2	2/2006	Weber et al.
7,003,339	B2	2/2006	Diab et al.
7,015,451	B2	3/2006	Dalke et al.
7,024,233	B2	4/2006	Ali et al.
7,027,849	B2	4/2006	Al-Ali
7,030,749	B2	4/2006	Al-Ali
7,039,449	B2	5/2006	Al-Ali
7,041,060	B2	5/2006	Flaherty et al.
7,044,918	B2	5/2006	Diab
7,067,893	B2	6/2006	Mills et al.
D526,719	S	8/2006	Richie, Jr. et al.
7,096,052	B2	8/2006	Mason et al.
7,096,054	B2	8/2006	Abdul-Hafiz et al.
7,096,060	B2	8/2006	Arand et al.
D529,616	S	10/2006	Deros et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,132,641 B2 11/2006 Schulz et al.
7,133,710 B2 11/2006 Acosta et al.
7,142,901 B2 11/2006 Kiani et al.
7,149,561 B2 12/2006 Diab
7,186,966 B2 3/2007 Al-Ali
7,190,261 B2 3/2007 Al-Ali
7,194,306 B1 3/2007 Turcott
7,215,984 B2 5/2007 Diab
7,215,986 B2 5/2007 Diab
7,221,971 B2 5/2007 Diab
7,225,006 B2 5/2007 Al-Ali et al.
7,225,007 B2 5/2007 Al-Ali
RE39,672 E 6/2007 Shehada et al.
7,239,905 B2 7/2007 Kiani-Azarbayjany et al.
7,245,953 B1 7/2007 Parker
7,254,429 B2 8/2007 Schurman et al.
7,254,431 B2 8/2007 Al-Ali
7,254,433 B2 8/2007 Diab et al.
7,254,434 B2 8/2007 Schulz et al.
7,267,652 B2 9/2007 Coyle et al.
7,272,425 B2 9/2007 Al-Ali
7,274,955 B2 9/2007 Kiani et al.
D554,263 S 10/2007 Al-Ali
7,280,858 B2 10/2007 Al-Ali et al.
7,289,835 B2 10/2007 Mansfield et al.
7,292,883 B2 11/2007 De Felice et al.
7,295,866 B2 11/2007 Al-Ali
7,328,053 B1 2/2008 Diab et al.
7,332,784 B2 2/2008 Mills et al.
7,340,287 B2 3/2008 Mason et al.
7,341,559 B2 3/2008 Schulz et al.
7,343,186 B2 3/2008 Lamego et al.
D566,282 S 4/2008 Al-Ali et al.
7,355,512 B1 4/2008 Al-Ali
7,356,365 B2 4/2008 Schurman
7,361,146 B1 4/2008 Bharmi et al.
7,371,981 B2 5/2008 Abdul-Hafiz
7,373,193 B2 5/2008 Al-Ali et al.
7,373,194 B2 5/2008 Weber et al.
7,376,453 B1 5/2008 Diab et al.
7,377,794 B2 5/2008 Ali et al.
7,377,899 B2 5/2008 Weber et al.
7,383,070 B2 6/2008 Diab et al.
7,395,158 B2 7/2008 Monfre et al.
7,398,115 B2 7/2008 Lynn
7,403,806 B2 7/2008 Norris
7,415,297 B2 8/2008 Al-Ali et al.
7,428,432 B2 9/2008 Ali et al.
7,438,683 B2 10/2008 Al-Ali et al.
7,440,787 B2 10/2008 Diab
7,454,240 B2 11/2008 Diab et al.
7,467,002 B2 12/2008 Weber et al.
7,469,157 B2 12/2008 Diab et al.
7,471,969 B2 12/2008 Diab et al.
7,471,971 B2 12/2008 Diab et al.
7,483,729 B2 1/2009 Al-Ali et al.
7,483,730 B2 1/2009 Diab et al.
7,489,958 B2 2/2009 Diab et al.
7,496,391 B2 2/2009 Diab et al.
7,496,393 B2 2/2009 Diab et al.
D587,657 S 3/2009 Al-Ali et al.
7,499,741 B2 3/2009 Diab et al.
7,499,835 B2 3/2009 Weber et al.
7,500,950 B2 3/2009 Al-Ali et al.
7,509,154 B2 3/2009 Diab et al.
7,509,494 B2 3/2009 Al-Ali
7,510,849 B2 3/2009 Schurman et al.
7,514,725 B2 4/2009 Wojtczuk et al.
7,519,406 B2 4/2009 Blank et al.
7,526,328 B2 4/2009 Diab et al.
D592,507 S 5/2009 Wachman et al.
7,530,942 B1 5/2009 Diab
7,530,949 B2 5/2009 Al Ali et al.
7,530,955 B2 5/2009 Diab et al.
7,539,533 B2 5/2009 Tran
7,563,110 B2 7/2009 Al-Ali et al.
7,593,230 B2 9/2009 Abul-Haj et al.
7,596,398 B2 9/2009 Al-Ali et al.
7,606,608 B2 10/2009 Blank et al.
7,618,375 B2 11/2009 Flaherty
7,620,674 B2 11/2009 Ruchti et al.
D606,659 S 12/2009 Kiani et al.
7,629,039 B2 12/2009 Eckerbom et al.
7,640,140 B2 12/2009 Ruchti et al.
7,647,083 B2 1/2010 Al-Ali et al.
D609,193 S 2/2010 Al-Ali et al.
D614,305 S 4/2010 Al-Ali et al.
7,690,378 B1 4/2010 Turcott
7,697,966 B2 4/2010 Monfre et al.
7,698,105 B2 4/2010 Ruchti et al.
RE41,317 E 5/2010 Parker
RE41,333 E 5/2010 Blank et al.
7,729,733 B2 6/2010 Al-Ali et al.
7,734,320 B2 6/2010 Al-Ali
7,761,127 B2 7/2010 Al-Ali et al.
7,761,128 B2 7/2010 Al-Ali et al.
7,764,982 B2 7/2010 Dalke et al.
D621,516 S 8/2010 Kiani et al.
7,791,155 B2 9/2010 Diab
7,801,581 B2 9/2010 Diab
7,822,452 B2 10/2010 Schurman et al.
RE41,912 E 11/2010 Parker
7,844,313 B2 11/2010 Kiani et al.
7,844,314 B2 11/2010 Al-Ali
7,844,315 B2 11/2010 Al-Ali
7,865,222 B2 1/2011 Weber et al.
7,873,497 B2 1/2011 Weber et al.
7,880,606 B2 2/2011 Al-Ali
7,880,626 B2 2/2011 Al-Ali et al.
7,891,355 B2 2/2011 Al-Ali et al.
7,894,868 B2 2/2011 Al-Ali et al.
7,899,507 B2 3/2011 Al-Ali et al.
7,899,518 B2 3/2011 Trepagnier et al.
7,904,132 B2 3/2011 Weber et al.
7,909,772 B2 3/2011 Popov et al.
7,910,875 B2 3/2011 Al-Ali
7,919,713 B2 4/2011 Al-Ali et al.
7,937,128 B2 5/2011 Al-Ali
7,937,129 B2 5/2011 Mason et al.
7,937,130 B2 5/2011 Diab et al.
7,941,199 B2 5/2011 Kiani
7,951,086 B2 5/2011 Flaherty et al.
7,957,780 B2 6/2011 Lamego et al.
7,962,188 B2 6/2011 Kiani et al.
7,962,190 B1 6/2011 Diab et al.
7,976,472 B2 7/2011 Kiani
7,988,637 B2 8/2011 Diab
7,990,382 B2 8/2011 Kiani
7,991,446 B2 8/2011 Al-Ali et al.
8,000,761 B2 8/2011 Al-Ali
8,008,088 B2 8/2011 Bellott et al.
RE42,753 E 9/2011 Kiani-Azarbayjany et al.
8,019,400 B2 9/2011 Diab et al.
8,028,701 B2 10/2011 Al-Ali et al.
8,029,765 B2 10/2011 Bellott et al.
8,036,727 B2 10/2011 Schurman et al.
8,036,728 B2 10/2011 Diab et al.
8,046,040 B2 10/2011 Ali et al.
8,046,041 B2 10/2011 Diab et al.
8,046,042 B2 10/2011 Diab et al.
8,048,040 B2 11/2011 Kiani
8,050,728 B2 11/2011 Al-Ali et al.
RE43,169 E 2/2012 Parker
8,118,620 B2 2/2012 Al-Ali et al.
8,126,528 B2 2/2012 Diab et al.
8,128,572 B2 3/2012 Diab et al.
8,130,105 B2 3/2012 Al-Ali et al.
8,145,287 B2 3/2012 Diab et al.
8,150,487 B2 4/2012 Diab et al.
8,175,672 B2 5/2012 Parker
8,180,420 B2 5/2012 Diab et al.
8,182,443 B1 5/2012 Kiani
8,185,180 B2 5/2012 Diab et al.
8,190,223 B2 5/2012 Al-Ali et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,190,227 B2 5/2012 Diab et al.
8,203,438 B2 6/2012 Kiani et al.
8,203,704 B2 6/2012 Merritt et al.
8,204,566 B2 6/2012 Schurman et al.
8,219,172 B2 7/2012 Schurman et al.
8,224,411 B2 7/2012 Al-Ali et al.
8,228,181 B2 7/2012 Al-Ali
8,229,532 B2 7/2012 Davis
8,229,533 B2 7/2012 Diab et al.
8,233,955 B2 7/2012 Al-Ali et al.
8,244,325 B2 8/2012 Al-Ali et al.
8,255,026 B1 8/2012 Al-Ali
8,255,027 B2 8/2012 Al-Ali et al.
8,255,028 B2 8/2012 Al-Ali et al.
8,260,577 B2 9/2012 Weber et al.
8,265,723 B1 9/2012 McHale et al.
8,274,360 B2 9/2012 Sampath et al.
8,280,473 B2 10/2012 Al-Ali
8,301,217 B2 10/2012 Al-Ali et al.
8,306,596 B2 11/2012 Schurman et al.
8,310,336 B2 11/2012 Muhsin et al.
8,315,683 B2 11/2012 Al-Ali et al.
RE43,860 E 12/2012 Parker
8,337,403 B2 12/2012 Al-Ali et al.
8,346,330 B2 1/2013 Lamego
8,353,842 B2 1/2013 Al-Ali et al.
8,355,766 B2 1/2013 MacNeish, III et al.
8,359,080 B2 1/2013 Diab et al.
8,364,223 B2 1/2013 Al-Ali et al.
8,364,226 B2 1/2013 Diab et al.
8,374,665 B2 2/2013 Lamego
8,385,995 B2 2/2013 Al-ali et al.
8,385,996 B2 2/2013 Smith et al.
8,388,353 B2 3/2013 Kiani et al.
8,399,822 B2 3/2013 Al-Ali
8,401,602 B2 3/2013 Kiani
8,405,608 B2 3/2013 Al-Ali et al.
8,414,499 B2 4/2013 Al-Ali et al.
8,418,524 B2 4/2013 Al-Ali
8,423,106 B2 4/2013 Lamego et al.
8,428,967 B2 4/2013 Olsen et al.
8,430,817 B1 4/2013 Al-Ali et al.
8,437,825 B2 5/2013 Dalvi et al.
8,455,290 B2 6/2013 Siskavich
8,457,703 B2 6/2013 Al-Ali
8,457,707 B2 6/2013 Kiani
8,463,349 B2 6/2013 Diab et al.
8,466,286 B2 6/2013 Bellot et al.
8,471,713 B2 6/2013 Poeze et al.
8,473,020 B2 6/2013 Kiani et al.
8,478,538 B2 7/2013 McGonigle et al.
8,483,787 B2 7/2013 Al-Ali et al.
8,489,364 B2 7/2013 Weber et al.
8,498,684 B2 7/2013 Weber et al.
8,504,128 B2 8/2013 Blank et al.
8,509,867 B2 8/2013 Workman et al.
8,515,509 B2 8/2013 Bruinsma et al.
8,523,781 B2 9/2013 Al-Ali
8,529,301 B2 9/2013 Al-Ali et al.
8,532,727 B2 9/2013 Ali et al.
8,532,728 B2 9/2013 Diab et al.
D692,145 S 10/2013 Al-Ali et al.
8,547,209 B2 10/2013 Kiani et al.
8,548,548 B2 10/2013 Al-Ali
8,548,549 B2 10/2013 Schurman et al.
8,548,550 B2 10/2013 Al-Ali et al.
8,560,032 B2 10/2013 Al-Ali et al.
8,560,034 B1 10/2013 Diab et al.
8,570,167 B2 10/2013 Al-Ali
8,570,503 B2 10/2013 Vo et al.
8,571,617 B2 10/2013 Reichgott et al.
8,571,618 B1 10/2013 Lamego et al.
8,571,619 B2 10/2013 Al-Ali et al.
8,584,345 B2 10/2013 Al-Ali et al.
8,577,431 B2 11/2013 Lamego et al.
8,581,732 B2 11/2013 Al-Ali et al.
8,588,880 B2 11/2013 Abdul-Hafiz et al.
8,597,274 B2 12/2013 Sloan
8,600,467 B2 12/2013 Al-Ali et al.
8,606,342 B2 12/2013 Diab
8,622,902 B2 1/2014 Woehrle
8,626,255 B2 1/2014 Al-Ali et al.
8,630,691 B2 1/2014 Lamego et al.
8,634,889 B2 1/2014 Al-Ali et al.
8,641,631 B2 2/2014 Sierra et al.
8,652,060 B2 2/2014 Al-Ali
8,663,107 B2 3/2014 Kiani
8,666,468 B1 3/2014 Al-Ali
8,667,967 B2 3/2014 Al-Ali et al.
8,670,811 B2 3/2014 O'Reilly
8,670,814 B2 3/2014 Diab et al.
8,676,286 B2 3/2014 Weber et al.
8,682,407 B2 3/2014 Al-Ali
RE44,823 E 4/2014 Parker
RE44,875 E 4/2014 Kiani et al.
8,688,183 B2 4/2014 Bruinsma et al.
8,690,799 B2 4/2014 Telfort et al.
8,700,112 B2 4/2014 Kiani
8,702,627 B2 4/2014 Telfort et al.
8,706,179 B2 4/2014 Parker
8,712,494 B1 4/2014 MacNeish, III et al.
8,715,206 B2 5/2014 Telfort et al.
8,718,735 B2 5/2014 Lamego et al.
8,718,737 B2 5/2014 Diab et al.
8,718,738 B2 5/2014 Blank et al.
8,720,249 B2 5/2014 Al-Ali
8,721,541 B2 5/2014 Al-Ali et al.
8,721,542 B2 5/2014 Al-Ali et al.
8,723,677 B1 5/2014 Kiani
8,740,792 B1 6/2014 Kiani et al.
8,754,776 B2 6/2014 Poeze et al.
8,755,535 B2 6/2014 Telfort et al.
8,755,856 B2 6/2014 Diab et al.
8,755,872 B1 6/2014 Marinow
8,761,850 B2 6/2014 Lamego
8,764,671 B2 7/2014 Kiani
8,768,423 B2 7/2014 Shakespeare et al.
8,771,204 B2 7/2014 Telfort et al.
8,777,634 B2 7/2014 Kiani et al.
8,781,543 B2 7/2014 Diab et al.
8,781,544 B2 7/2014 Al-Ali et al.
8,781,549 B2 7/2014 Al-Ali et al.
8,788,003 B2 7/2014 Schurman et al.
8,790,268 B2 7/2014 Al-Ali
8,792,949 B2 7/2014 Baker
8,801,613 B2 8/2014 Al-Ali et al.
8,821,397 B2 9/2014 Al-Ali et al.
8,821,415 B2 9/2014 Al-Ali et al.
8,830,449 B1 9/2014 Lamego et al.
8,831,700 B2 9/2014 Schurman et al.
8,840,549 B2 9/2014 Al-Ali et al.
8,847,740 B2 9/2014 Kiani et al.
8,849,365 B2 9/2014 Smith et al.
8,852,094 B2 10/2014 Al-Ali et al.
8,852,994 B2 10/2014 Wojtczuk et al.
8,868,147 B2 10/2014 Stippick et al.
8,868,150 B2 10/2014 Al-Ali et al.
8,870,792 B2 10/2014 Al-Ali et al.
8,886,271 B2 11/2014 Kiani et al.
8,888,539 B2 11/2014 Al-Ali et al.
8,888,708 B2 11/2014 Diab et al.
8,892,180 B2 11/2014 Weber et al.
8,897,847 B2 11/2014 Al-Ali
8,909,310 B2 12/2014 Lamego
8,911,377 B2 12/2014 Al-Ali
8,912,909 B2 12/2014 Al-Ali et al.
8,920,317 B2 12/2014 Al-Ali et al.
8,921,699 B2 12/2014 Al-Ali et al.
8,922,382 B2 12/2014 Al-Ali et al.
8,929,964 B2 1/2015 Al-Ali et al.
8,942,777 B2 1/2015 Diab et al.
8,948,834 B2 2/2015 Diab et al.
8,948,835 B2 2/2015 Diab
8,965,471 B2 2/2015 Lamego

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,983,564 B2 3/2015 Al-Ali
8,989,831 B2 3/2015 Al-Ali et al.
8,996,085 B2 3/2015 Kiani et al.
8,998,809 B2 4/2015 Kiani
9,028,429 B2 5/2015 Telfort et al.
9,037,207 B2 5/2015 Al-Ali et al.
9,060,721 B2 6/2015 Reichgott et al.
9,066,666 B2 6/2015 Kiani
9,066,680 B1 6/2015 Al-Ali et al.
9,072,474 B2 7/2015 Al-Ali et al.
9,078,560 B2 7/2015 Schurman et al.
9,084,569 B2 7/2015 Weber et al.
9,095,316 B2 8/2015 Welch et al.
9,106,038 B2 8/2015 Telfort et al.
9,107,625 B2 8/2015 Telfort et al.
9,107,626 B2 8/2015 Al-Ali et al.
9,113,831 B2 8/2015 Al-Ali
9,113,832 B2 8/2015 Al-Ali
9,119,595 B2 9/2015 Lamego
9,131,881 B2 9/2015 Diab et al.
9,131,882 B2 9/2015 Al-Ali et al.
9,131,883 B2 9/2015 Al-Ali
9,131,917 B2 9/2015 Telfort et al.
9,135,398 B2 9/2015 Kaib
9,138,180 B1 9/2015 Coverston et al.
9,138,182 B2 9/2015 Al-Ali et al.
9,138,192 B2 9/2015 Weber et al.
9,142,117 B2 9/2015 Muhsin et al.
9,153,112 B1 10/2015 Kiani et al.
9,153,121 B2 10/2015 Kiani et al.
9,161,696 B2 10/2015 Al-Ali et al.
9,161,713 B2 10/2015 Al-Ali et al.
9,167,995 B2 10/2015 Lamego et al.
9,176,141 B2 11/2015 Al-Ali et al.
9,186,102 B2 11/2015 Bruinsma et al.
9,192,312 B2 11/2015 Al-Ali
9,192,329 B2 11/2015 Al-Ali
9,192,351 B1 11/2015 Telfort et al.
9,195,385 B2 11/2015 Al-Ali et al.
9,211,072 B2 12/2015 Kiani
9,211,095 B1 12/2015 Al-Ali
9,218,454 B2 12/2015 Kiani et al.
9,220,440 B2 12/2015 Addison et al.
9,226,696 B2 1/2016 Kiani
9,241,662 B2 1/2016 Al-Ali et al.
9,245,668 B1 1/2016 Vo et al.
9,259,185 B2 1/2016 Abdul-Hafiz et al.
9,267,572 B2 2/2016 Barker et al.
9,277,880 B2 2/2016 Poeze et al.
9,289,167 B2 3/2016 Diab et al.
9,295,421 B2 3/2016 Kiani et al.
9,307,928 B1 4/2016 Al-Ali et al.
9,323,894 B2 4/2016 Kiani
D755,392 S 5/2016 Hwang et al.
9,326,712 B1 5/2016 Kiani
9,333,316 B2 5/2016 Kiani
9,339,220 B2 5/2016 Lamego et al.
9,341,565 B2 5/2016 Lamego et al.
9,351,673 B2 5/2016 Diab et al.
9,351,675 B2 5/2016 Al-Ali et al.
9,364,181 B2 6/2016 Kiani et al.
9,368,671 B2 6/2016 Wojtczuk et al.
9,370,325 B2 6/2016 Al-Ali et al.
9,370,326 B2 6/2016 McHale et al.
9,370,335 B2 6/2016 Al-ali et al.
9,375,185 B2 6/2016 Ali et al.
9,378,637 B2 6/2016 Kaib
9,386,953 B2 7/2016 Al-Ali
9,386,961 B2 7/2016 Al-Ali et al.
9,392,945 B2 7/2016 Al-Ali et al.
9,397,448 B2 7/2016 Al-Ali et al.
9,408,542 B1 8/2016 Kinast et al.
9,436,645 B2 9/2016 Al-Ali et al.
9,445,759 B1 9/2016 Lamego et al.
9,466,919 B2 10/2016 Kiani et al.
9,474,474 B2 10/2016 Lamego et al.
9,480,422 B2 11/2016 Al-Ali
9,480,435 B2 11/2016 Olsen
9,492,110 B2 11/2016 Al-Ali et al.
9,510,779 B2 12/2016 Poeze et al.
9,517,024 B2 12/2016 Kiani et al.
9,532,722 B2 1/2017 Lamego et al.
9,538,949 B2 1/2017 Al-Ali et al.
9,538,980 B2 1/2017 Telfort et al.
9,549,696 B2 1/2017 Lamego et al.
9,554,737 B2 1/2017 Schurman et al.
9,560,996 B2 2/2017 Kiani
9,560,998 B2 2/2017 Al-Ali et al.
9,566,019 B2 2/2017 Al-Ali et al.
9,579,039 B2 2/2017 Jansen et al.
9,591,975 B2 3/2017 Dalvi et al.
9,622,692 B2 4/2017 Lamego et al.
9,622,693 B2 4/2017 Diab
D788,312 S 5/2017 Al-Ali et al.
9,649,054 B2 5/2017 Lamego et al.
9,659,475 B2 5/2017 Kaib
9,697,928 B2 7/2017 Al-Ali et al.
9,717,458 B2 8/2017 Lamego et al.
9,724,016 B1 8/2017 Al-Ali et al.
9,724,024 B2 8/2017 Al-Ali
9,724,025 B1 8/2017 Kiani et al.
9,749,232 B2 8/2017 Sampath et al.
9,750,442 B2 9/2017 Olsen
9,750,461 B1 9/2017 Telfort
9,775,545 B2 10/2017 Al-Ali et al.
9,778,079 B1 10/2017 Al-Ali et al.
9,782,077 B2 10/2017 Lamego et al.
9,787,568 B2 10/2017 Lamego et al.
9,808,188 B1 11/2017 Perea et al.
9,839,379 B2 12/2017 Al-Ali et al.
9,839,381 B1 12/2017 Weber et al.
9,847,749 B2 12/2017 Kiani et al.
9,848,800 B1 12/2017 Lee
9,861,298 B2 1/2018 Eckerbom et al.
9,861,305 B1 1/2018 Weber et al.
9,877,650 B2 1/2018 Muhsin et al.
9,891,079 B2 2/2018 Dalvi
9,924,897 B1 3/2018 Abdul-Hafiz
9,936,917 B2 4/2018 Poeze et al.
9,955,937 B2 5/2018 Telfort
9,965,946 B2 5/2018 Al-Ali et al.
9,968,266 B2 5/2018 An et al.
D820,865 S 6/2018 Muhsin et al.
9,986,952 B2 6/2018 Dalvi et al.
D822,215 S 7/2018 Al-Ali et al.
D822,216 S 7/2018 Barker et al.
10,010,276 B2 7/2018 Al-Ali et al.
10,086,138 B1 10/2018 Novak, Jr.
10,111,591 B2 10/2018 Dyell et al.
D833,624 S 11/2018 DeJong et al.
10,123,729 B2 11/2018 Dyell et al.
D835,282 S 12/2018 Barker et al.
D835,283 S 12/2018 Barker et al.
D835,284 S 12/2018 Barker et al.
D835,285 S 12/2018 Barker et al.
10,149,616 B2 12/2018 Al-Ali et al.
10,154,815 B2 12/2018 Al-Ali et al.
10,159,412 B2 12/2018 Lamego et al.
10,188,348 B2 1/2019 Al-Ali et al.
RE47,218 E 2/2019 Al-Ali
RE47,244 E 2/2019 Kiani et al.
RE47,249 E 2/2019 Kiani et al.
10,205,291 B2 2/2019 Scruggs et al.
10,226,187 B2 3/2019 Al-Ali et al.
10,231,657 B2 3/2019 Al-Ali et al.
10,231,670 B2 3/2019 Blank et al.
RE47,353 E 4/2019 Kiani et al.
10,279,247 B2 5/2019 Kiani
10,292,664 B2 5/2019 Al-Ali
10,299,720 B2 5/2019 Brown et al.
10,327,337 B2 6/2019 Schmidt et al.
10,327,713 B2 6/2019 Barker et al.
10,332,630 B2 6/2019 Al-Ali
10,383,520 B2 8/2019 Wojtczuk et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

10,383,527	B2	8/2019	Al-Ali
10,388,120	B2	8/2019	Muhsin et al.
D864,120	S	10/2019	Forrest et al.
10,441,181	B1	10/2019	Telfort et al.
10,441,196	B2	10/2019	Eckerbom et al.
10,448,844	B2	10/2019	Al-Ali et al.
10,448,871	B2	10/2019	Al-Ali et al.
10,456,038	B2	10/2019	Lamego et al.
10,463,340	B2	11/2019	Telfort et al.
10,471,159	B1	11/2019	Lapotko et al.
10,505,311	B2	12/2019	Al-Ali et al.
10,524,738	B2	1/2020	Olsen
10,532,174	B2	1/2020	Al-Ali
10,537,285	B2	1/2020	Shreim et al.
10,542,903	B2	1/2020	Al-Ali et al.
10,555,678	B2	2/2020	Dalvi et al.
10,568,553	B2	2/2020	O'Neil et al.
RE47,882	E	3/2020	Al-Ali
10,608,817	B2	3/2020	Haider et al.
D880,477	S	4/2020	Forrest et al.
10,617,302	B2	4/2020	Al-Ali et al.
10,617,335	B2	4/2020	Al-Ali et al.
10,637,181	B2	4/2020	Al-Ali et al.
D887,548	S	6/2020	Abdul-Hafiz et al.
D887,549	S	6/2020	Abdul-Hafiz et al.
10,667,764	B2	6/2020	Ahmed et al.
D890,708	S	7/2020	Forrest et al.
10,721,785	B2	7/2020	Al-Ali
10,736,518	B2	8/2020	Al-Ali et al.
10,750,984	B2	8/2020	Pauley et al.
D897,098	S	9/2020	Al-Ali
10,779,098	B2	9/2020	Iswanto et al.
10,827,961	B1	11/2020	Iyengar et al.
10,828,007	B1	11/2020	Telfort et al.
10,832,818	B2	11/2020	Muhsin et al.
10,849,554	B2	12/2020	Shreim et al.
10,856,750	B2	12/2020	Indorf et al.
D906,970	S	1/2021	Forrest et al.
10,918,281	B2	2/2021	Al-Ali et al.
10,932,705	B2	3/2021	Muhsin et al.
10,932,729	B2	3/2021	Kiani et al.
10,939,878	B2	3/2021	Kiani et al.
D916,135	S	4/2021	Indorf et al.
D917,550	S	4/2021	Indorf et al.
D917,564	S	4/2021	Indorf et al.
D917,704	S	4/2021	Al-Ali et al.
10,987,066	B2	4/2021	Chandran et al.
10,991,135	B2	4/2021	Al-Ali et al.
D919,094	S	5/2021	Al-Ali et al.
D919,100	S	5/2021	Al-Ali et al.
11,006,867	B2	5/2021	Al-Ali
D921,202	S	6/2021	Al-Ali et al.
11,024,064	B2	6/2021	Muhsin et al.
11,026,604	B2	6/2021	Chen et al.
D925,597	S	7/2021	Chandran et al.
D927,699	S	8/2021	Al-Ali et al.
11,076,777	B2	8/2021	Lee et al.
11,114,188	B2	9/2021	Poeze et al.
D933,232	S	10/2021	Al-Ali et al.
11,145,408	B2	10/2021	Sampath et al.
11,147,518	B1	10/2021	Al-Ali et al.
11,185,262	B2	11/2021	Al-Ali et al.
11,191,484	B2	12/2021	Kiani et al.
2001/0002206	A1	5/2001	Diab et al.
2001/0034477	A1	10/2001	Mansfield et al.
2001/0039483	A1	11/2001	Brand et al.
2002/0010401	A1	1/2002	Bushmakin et al.
2002/0058864	A1	5/2002	Mansfield et al.
2002/0133080	A1	9/2002	Apruzzese et al.
2002/0193670	A1	12/2002	Garfield et al.
2003/0013975	A1	1/2003	Kiani
2003/0015368	A1	1/2003	Cybulski et al.
2003/0018243	A1	1/2003	Gerhardt et al.
2003/0065269	A1	4/2003	Vetter
2003/0076494	A1	4/2003	Bonin et al.
2003/0144582	A1	7/2003	Cohen et al.
2003/0156288	A1	8/2003	Barnum et al.
2003/0158466	A1	8/2003	Lynn et al.
2003/0163033	A1	8/2003	Dekker et al.
2003/0163054	A1	8/2003	Dekker
2003/0212312	A1	11/2003	Coffin, IV et al.
2004/0010202	A1	1/2004	Nakatani
2004/0034293	A1	2/2004	Kimball
2004/0039273	A1	2/2004	Terry
2004/0059203	A1	3/2004	Guerrero
2004/0060362	A1	4/2004	Kjellmann et al.
2004/0087846	A1	5/2004	Wasserman
2004/0106163	A1	6/2004	Workman, Jr. et al.
2004/0133087	A1	7/2004	Ali et al.
2004/0158162	A1	8/2004	Narimatsu
2004/0225332	A1	11/2004	Gebhardt
2004/0260186	A1	12/2004	Dekker
2005/0010166	A1	1/2005	Hickle
2005/0027205	A1	2/2005	Tarassenko et al.
2005/0048456	A1	3/2005	Chefd'hotel et al.
2005/0055276	A1	3/2005	Kiani et al.
2005/0070774	A1	3/2005	Addison et al.
2005/0107699	A1	5/2005	Loftman
2005/0116820	A1	6/2005	Goldreich
2005/0177096	A1	8/2005	Bollish et al.
2005/0199056	A1	9/2005	Strong
2005/0234317	A1	10/2005	Kiani
2006/0047215	A1	3/2006	Newman et al.
2006/0073719	A1	4/2006	Kiani
2006/0129216	A1	6/2006	Hastings et al.
2006/0149144	A1	7/2006	Lynn et al.
2006/0155206	A1	7/2006	Lynn
2006/0155207	A1	7/2006	Lynn et al.
2006/0161071	A1	7/2006	Lynn et al.
2006/0189871	A1	8/2006	Al-Ali et al.
2006/0189880	A1	8/2006	Lynn et al.
2006/0195041	A1	8/2006	Lynn et al.
2006/0235324	A1	10/2006	Lynn
2006/0238333	A1	10/2006	Welch et al.
2006/0241510	A1	10/2006	Halperin et al.
2006/0258921	A1	11/2006	Addison et al.
2007/0032732	A1	2/2007	Shelley et al.
2007/0055198	A1	3/2007	O'Mahony et al.
2007/0073116	A1	3/2007	Kiani et al.
2007/0093721	A1	4/2007	Lynn et al.
2007/0129643	A1	6/2007	Kwok et al.
2007/0129647	A1	6/2007	Lynn
2007/0135725	A1	6/2007	Hatlestad
2007/0149860	A1	6/2007	Lynn et al.
2007/0163353	A1	7/2007	Lee et al.
2007/0180140	A1	8/2007	Welch et al.
2007/0185397	A1	8/2007	Govari et al.
2007/0213619	A1	9/2007	Linder
2007/0239057	A1	10/2007	Pu et al.
2007/0244377	A1	10/2007	Cozad et al.
2007/0282212	A1	12/2007	Sierra et al.
2008/0013747	A1	1/2008	Tran
2008/0039735	A1	2/2008	Hickerson
2008/0064965	A1	3/2008	Jay et al.
2008/0067132	A1	3/2008	Ross et al.
2008/0071185	A1	3/2008	Beck et al.
2008/0076972	A1	3/2008	Dorogusker et al.
2008/0079299	A1	4/2008	Jackson
2008/0094228	A1	4/2008	Welch et al.
2008/0119716	A1	5/2008	Boric-Lubecke et al.
2008/0161878	A1	7/2008	Tehrani et al.
2008/0167541	A1	7/2008	Takala et al.
2008/0177195	A1	7/2008	Armitstead
2008/0188733	A1	8/2008	Al-Ali
2008/0188760	A1	8/2008	Al-Ali
2008/0218153	A1	9/2008	Patel et al.
2008/0221418	A1	9/2008	Al-Ali et al.
2008/0221512	A1	9/2008	Da Silva et al.
2008/0275349	A1	11/2008	Halperin et al.
2008/0304580	A1	12/2008	Ichiyama
2009/0018409	A1	1/2009	Banet et al.
2009/0018429	A1	1/2009	Saliga et al.
2009/0018453	A1	1/2009	Banet et al.
2009/0036759	A1	2/2009	Ault et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2009/0043179	A1	2/2009	Melker et al.	
2009/0093687	A1	4/2009	Telfort et al.	
2009/0095926	A1	4/2009	MacNeish, III	
2009/0112096	A1	4/2009	Tamura	
2009/0160654	A1	6/2009	Yang	
2009/0167332	A1	7/2009	Forbes	
2009/0187065	A1	7/2009	Basinger	
2009/0227882	A1	9/2009	Foo	
2009/0240119	A1	9/2009	Schwaibold et al.	
2009/0247848	A1	10/2009	Baker	
2009/0247984	A1	10/2009	Lamego et al.	
2009/0275844	A1	11/2009	Al-Ali	
2009/0299157	A1	12/2009	Telfort et al.	
2009/0312612	A1*	12/2009	Rantala	A61B 5/0205 600/301
2009/0326349	A1	12/2009	McGonigle et al.	
2010/0004518	A1	1/2010	Vo et al.	
2010/0004552	A1	1/2010	Zhang et al.	
2010/0014761	A1*	1/2010	Addison	G06K 9/00516 382/207
2010/0016682	A1	1/2010	Schluess et al.	
2010/0016693	A1	1/2010	Addison	
2010/0030040	A1	2/2010	Poeze et al.	
2010/0099964	A1	4/2010	O'Reilly et al.	
2010/0130873	A1	5/2010	Yuen	
2010/0204550	A1	8/2010	Heneghan	
2010/0234718	A1	9/2010	Sampath et al.	
2010/0261979	A1	10/2010	Kiani	
2010/0270257	A1	10/2010	Wachman et al.	
2010/0274099	A1	10/2010	Telfort et al.	
2010/0295686	A1	11/2010	Sloan	
2010/0298661	A1	11/2010	McCombie et al.	
2010/0298730	A1	11/2010	Taressenko et al.	
2010/0324377	A1	12/2010	Woehrle	
2010/0331903	A1	12/2010	Zhang	
2011/0001605	A1	1/2011	Kiani	
2011/0009710	A1	1/2011	Kroeger et al.	
2011/0028806	A1	2/2011	Merritt et al.	
2011/0028809	A1	2/2011	Goodman	
2011/0040197	A1	2/2011	Welch et al.	
2011/0040713	A1	2/2011	Colman	
2011/0066062	A1	3/2011	Banet et al.	
2011/0074409	A1	3/2011	Stoughton	
2011/0082711	A1	4/2011	Poeze et al.	
2011/0087081	A1	4/2011	Kiani et al.	
2011/0105854	A1	5/2011	Kiani et al.	
2011/0118561	A1	5/2011	Tari et al.	
2011/0118573	A1	5/2011	McKenna	
2011/0125060	A1	5/2011	Telfort et al.	
2011/0137297	A1	6/2011	Kiani et al.	
2011/0172498	A1	7/2011	Olsen et al.	
2011/0172561	A1	7/2011	Kiani et al.	
2011/0208015	A1	8/2011	Welch et al.	
2011/0209915	A1	9/2011	Telfort et al.	
2011/0213212	A1	9/2011	Al-Ali	
2011/0222371	A1	9/2011	Liu et al.	
2011/0230733	A1	9/2011	Al-Ali et al.	
2011/0237911	A1	9/2011	Lamego et al.	
2012/0016255	A1	1/2012	Masuo	
2012/0059267	A1	3/2012	Lamego et al.	
2012/0070013	A1	3/2012	Vau	
2012/0101344	A1	4/2012	Desjardins	
2012/0116175	A1	5/2012	Al-Ali et al.	
2012/0123231	A1	5/2012	O'Reilly	
2012/0165629	A1	6/2012	Merritt et al.	
2012/0179006	A1	7/2012	Jansen et al.	
2012/0209082	A1	8/2012	Al-Ali	
2012/0209084	A1	8/2012	Olsen et al.	
2012/0226117	A1	9/2012	Lamego et al.	
2012/0227739	A1	9/2012	Kiani	
2012/0253140	A1	10/2012	Addison et al.	
2012/0262298	A1	10/2012	Bohm	
2012/0283524	A1	11/2012	Kiani et al.	
2012/0296178	A1	11/2012	Lamego et al.	
2012/0319816	A1	12/2012	Al-Ali	
2012/0330112	A1	12/2012	Lamego et al.	
2013/0023775	A1	1/2013	Lamego et al.	
2013/0045685	A1	2/2013	Kiani	
2013/0046204	A1	2/2013	Lamego	
2013/0041591	A1	3/2013	Lamego	
2013/0060147	A1	3/2013	Welch et al.	
2013/0096405	A1	4/2013	Garfio	
2013/0096936	A1	4/2013	Sampath et al.	
2013/0109935	A1	5/2013	Al-Ali et al.	
2013/0116578	A1	5/2013	An et al.	
2013/0128690	A1	5/2013	Gopalan	
2013/0137936	A1	5/2013	Baker, Jr. et al.	
2013/0162433	A1	6/2013	Muhsin et al.	
2013/0190581	A1	7/2013	Al-Ali et al.	
2013/0190595	A1	7/2013	Oraevsky	
2013/0197328	A1	8/2013	Diab et al.	
2013/0243021	A1	9/2013	Siskavich	
2013/0253334	A1	9/2013	Al-Ali et al.	
2013/0274571	A1	10/2013	Diab et al.	
2013/0296672	A1	11/2013	Dalvi et al.	
2013/0296726	A1	11/2013	Nievauer et al.	
2013/0317370	A1	11/2013	Dalvi et al.	
2013/0324808	A1	12/2013	Al-Ali et al.	
2013/0331670	A1	12/2013	Kiani	
2013/0338461	A1	12/2013	Lamego et al.	
2013/0345921	A1	12/2013	Al-Ali et al.	
2014/0012100	A1	1/2014	Lamego et al.	
2014/0025306	A1	1/2014	Weber et al.	
2014/0034353	A1	2/2014	Al-Ali et al.	
2014/0051953	A1	2/2014	Lamego et al.	
2014/0058230	A1	2/2014	Abdul-Hafiz et al.	
2014/0066783	A1	3/2014	Kiani et al.	
2014/0077956	A1	3/2014	Sampath et al.	
2014/0081100	A1	3/2014	Muhsin et al.	
2014/0081175	A1	3/2014	Telfort	
2014/0094667	A1	4/2014	Schurman et al.	
2014/0100434	A1	4/2014	Diab et al.	
2014/0114199	A1	4/2014	Lamego et al.	
2014/0120564	A1	5/2014	Workman et al.	
2014/0121482	A1	5/2014	Merritt et al.	
2014/0121483	A1	5/2014	Kiani	
2014/0127137	A1	5/2014	Bellott et al.	
2014/0128696	A1	5/2014	Al-Ali	
2014/0128699	A1	5/2014	Al-Ali et al.	
2014/0129702	A1	5/2014	Lamego et al.	
2014/0135588	A1	5/2014	Al-Ali et al.	
2014/0142401	A1	5/2014	Al-Ali et al.	
2014/0142402	A1	5/2014	Al-Ali et al.	
2014/0163344	A1	6/2014	Al-Ali	
2014/0163402	A1	6/2014	Lamego et al.	
2014/0166076	A1	6/2014	Kiani et al.	
2014/0171763	A1	6/2014	Diab	
2014/0180038	A1	6/2014	Kiani et al.	
2014/0180154	A1	6/2014	Sierra et al.	
2014/0180160	A1	6/2014	Brown et al.	
2014/0187973	A1	7/2014	Brown et al.	
2014/0194709	A1	7/2014	Al-Ali et al.	
2014/0194711	A1	7/2014	Al-Ali	
2014/0194766	A1	7/2014	Al-Ali et al.	
2014/0206963	A1	7/2014	Diab et al.	
2014/0213864	A1	7/2014	Abdul-Hafiz et al.	
2014/0243627	A1	8/2014	Diab et al.	
2014/0266790	A1	9/2014	Al-Ali et al.	
2014/0275808	A1	9/2014	Poeze et al.	
2014/0275835	A1	9/2014	Lamego et al.	
2014/0275871	A1	9/2014	Lamego et al.	
2014/0275872	A1	9/2014	Merritt et al.	
2014/0275881	A1	9/2014	Lamego et al.	
2014/0288400	A1	9/2014	Diab et al.	
2014/0296664	A1	10/2014	Bruinsma et al.	
2014/0303520	A1	10/2014	Telfort et al.	
2014/0309506	A1	10/2014	Lamego et al.	
2014/0316217	A1	10/2014	Purdon et al.	
2014/0316218	A1	10/2014	Purdon et al.	
2014/0316228	A1	10/2014	Blank et al.	
2014/0323825	A1	10/2014	Al-Ali et al.	
2014/0323897	A1	10/2014	Brown et al.	
2014/0323898	A1	10/2014	Purdon et al.	
2014/0330092	A1	11/2014	Al-Ali et al.	

(56) **References Cited**

U.S. PATENT DOCUMENTS

2014/0330098	A1	11/2014	Merritt et al.
2014/0330099	A1	11/2014	Al-Ali et al.
2014/0333440	A1	11/2014	Kiani
2014/0336481	A1	11/2014	Shakespeare et al.
2014/0343436	A1	11/2014	Kiani
2015/0005600	A1	1/2015	Blank et al.
2015/0011907	A1	1/2015	Purdon et al.
2015/0018650	A1	1/2015	Al-Ali et al.
2015/0073241	A1	3/2015	Lamego
2015/0080754	A1	3/2015	Purdon et al.
2015/0099950	A1	4/2015	Al-Ali et al.
2016/0196388	A1	7/2016	Lamego
2016/0283665	A1	9/2016	Sampath et al.
2016/0367173	A1	12/2016	Dalvi et al.
2017/0024748	A1	1/2017	Haider
2017/0042488	A1	2/2017	Muhsin
2017/0173632	A1	6/2017	Al-Ali
2017/0251974	A1	9/2017	Shreim et al.
2017/0311891	A1	11/2017	Kiani et al.
2018/0103874	A1	4/2018	Lee et al.
2018/0242926	A1	8/2018	Muhsin et al.
2018/0247353	A1	8/2018	Al-Ali et al.
2018/0247712	A1	8/2018	Muhsin et al.
2018/0256087	A1	9/2018	Al-Ali et al.
2018/0296161	A1	10/2018	Shreim et al.
2018/0300919	A1	10/2018	Muhsin et al.
2018/0310822	A1	11/2018	Indorf et al.
2018/0310823	A1	11/2018	Al-Ali et al.
2018/0317826	A1	11/2018	Muhsin et al.
2019/0015023	A1	1/2019	Monfre
2019/0117070	A1	4/2019	Muhsin et al.
2019/0200941	A1	7/2019	Chandran et al.
2019/0239787	A1	8/2019	Pauley et al.
2019/0320906	A1	10/2019	Olsen
2019/0374139	A1	12/2019	Kiani et al.
2019/0374173	A1	12/2019	Kiani et al.
2019/0374713	A1	12/2019	Kiani et al.
2020/0060869	A1	2/2020	Telfort et al.
2020/0111552	A1	4/2020	Ahmed
2020/0113435	A1	4/2020	Muhsin
2020/0113488	A1	4/2020	Al-Ali et al.
2020/0113496	A1	4/2020	Scruggs et al.
2020/0113497	A1	4/2020	Triman et al.
2020/0113520	A1	4/2020	Abdul-Hafiz et al.
2020/0138288	A1	5/2020	Al-Ali et al.
2020/0138368	A1	5/2020	Kiani et al.
2020/0163597	A1	5/2020	Dalvi et al.
2020/0196877	A1	6/2020	Vo et al.
2020/0253474	A1	8/2020	Muhsin et al.
2020/0253544	A1	8/2020	Belur Nagaraj et al.
2020/0275841	A1	9/2020	Telfort et al.
2020/0288983	A1	9/2020	Telfort et al.
2020/0321793	A1	10/2020	Al-Ali et al.
2020/0329983	A1	10/2020	Al-Ali et al.
2020/0329984	A1	10/2020	Al-Ali et al.
2020/0329993	A1	10/2020	Al-Ali et al.
2020/0330037	A1	10/2020	Al-Ali et al.
2021/0022628	A1	1/2021	Telfort et al.
2021/0104173	A1	4/2021	Pauley et al.
2021/0113121	A1	4/2021	Diab et al.
2021/0117525	A1	4/2021	Kiani et al.
2021/0118581	A1	4/2021	Kiani et al.
2021/0121582	A1	4/2021	Krishnamani et al.
2021/0161465	A1	6/2021	Barker et al.
2021/0236729	A1	8/2021	Kiani et al.
2021/0256267	A1	8/2021	Ranasinghe et al.
2021/0256835	A1	8/2021	Ranasinghe et al.
2021/0275101	A1	9/2021	Vo et al.
2021/0290060	A1	9/2021	Ahmed
2021/0290072	A1	9/2021	Forrest
2021/0290080	A1	9/2021	Ahmed
2021/0290120	A1	9/2021	Al-Ali
2021/0290177	A1	9/2021	Novak, Jr.
2021/0290184	A1	9/2021	Ahmed
2021/0296008	A1	9/2021	Novak, Jr.
2021/0330228	A1	10/2021	Olsen et al.
2021/0386382	A1	12/2021	Olsen et al.

FOREIGN PATENT DOCUMENTS

EP	0659058	1/1999
EP	1207536	5/2002
GB	2358546	11/1999
JP	6214898	1/1987
JP	01-309872	6/1998
JP	10-155755	6/1998
JP	2001-50713	5/1999
JP	2001-321347	11/2001
JP	2002-028138	1/2002
JP	2003-329719	11/2003
JP	2006-516000	6/2006
WO	WO 1994/005207	3/1994
WO	WO 1994/013207	6/1994
WO	WO 1995/029632	11/1995
WO	WO 1999/053277	10/1999
WO	WO 2000/010462	3/2000
WO	WO 2001/034033	5/2001
WO	WO 2001/078059	10/2001
WO	WO 2001/097691	12/2001
WO	WO 2002/003042	1/2002
WO	WO 2003/058646	7/2003
WO	WO 2003/087737	10/2003
WO	WO 2004/000111	12/2003
WO	WO 2004/004411	1/2004
WO	WO 2004/034898	4/2004
WO	WO 2005/096922	10/2005
WO	WO 2005/096931	10/2005
WO	WO 2005/099562	10/2005
WO	WO 2006/097866	9/2006
WO	WO 2008/017246	2/2008
WO	WO 2008/080469	7/2008
WO	WO 2008/148172	12/2008
WO	WO 2009/093159	7/2009
WO	WO 2009/137524	11/2009

OTHER PUBLICATIONS

US 9,579,050 B2, 02/2017, Al-Ali (withdrawn)

Cannesson et al., "Relation Between Respiratory Variations in Pulse Oximetry Plethysmographic Waveform Amplitude and Arterial Pulse Pressure in Ventilated Patients", Critical Care 2005, Aug. 23, 2005, pp. R562-R568.

GE Healthcare, "Transport Pro™ Patient Monitor Operator's Manual" Apr. 9, 2007, in 286 pages.

Hsu, "Signals and Systems", Schaum's Theory and Problems, 1995, Ch. 3, p. 121.

Szecsei, "Homework Helpers Basic Math and Pre-Algebra", 2006, The Career Press, p. 133.

Analog Devices, 12-Bit Serial Input Multiplying D/A Converter, Product Data Sheet, 2000.

Chambrin, M-C.; "Alarms in the intensive care unit: how can the number of false alarms be reduced?"; Critical Care Aug. 2001, vol. 5 No. 4; p. 1 -5.

Eldor et al., "A device for monitoring ventilation during anaesthesia; the paratracheal audible respiratory monitor", Canadian Journal of Anaesthesia, 1990, vol. 9, No. 1, p. 95-98.

Gorges, M. et al.; "Improving Alarm Performance in the Medical Intensive Care Unit Using Delays and Clinical Context"; Technology, Computing, and Simulation; vol. 108, No. 5, May 2009; p. 1546-1552.

Imhoff, M et al.; "Alarm Algorithms in Critical Care Monitoring"; Anesth Analg 2006;102:1525-37.

International Search Report & Written Opinion, PCT Application PCT/US2010/052758, dated Feb. 10, 2011; 12 pages.

International Search Report & Written Opinion, PCT Application PCT/US2010/058981, dated Feb. 17, 2011; 11 pages.

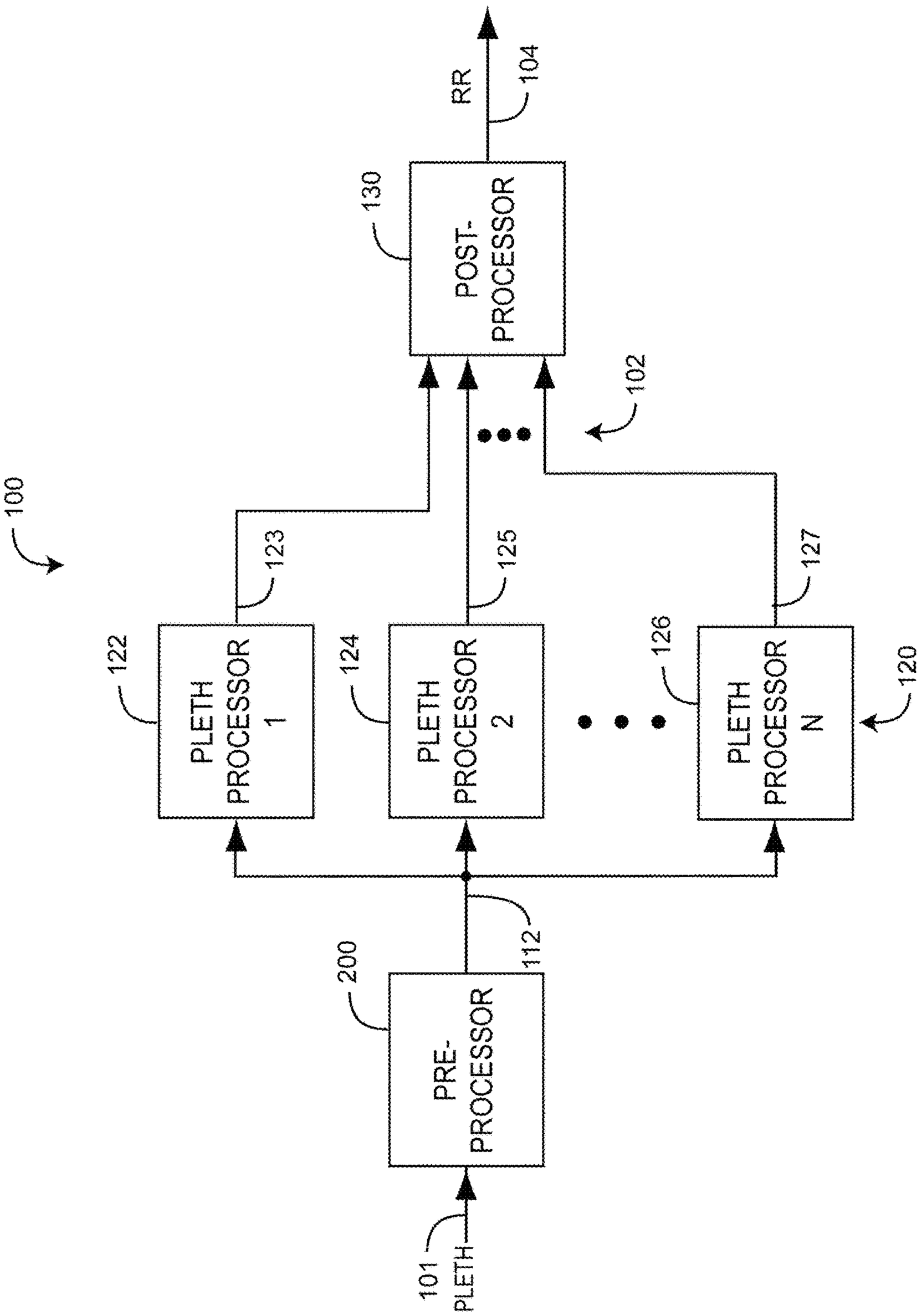
International Search Report and Written Opinion issued in application No. PCT/US2010/052756 dated Feb. 6, 2012.

(56) **References Cited**

OTHER PUBLICATIONS

International Search Report, PCT Application PCT/CA2003/000536, dated Dec. 11, 2003; 2 pages.
International Search Report, PCT Application PCT/US2009/069287, dated Mar. 30, 2010; 7 pages.
Japanese Office Action for JP Application No. 2007-506626 dated Mar. 1, 2011.
Sierra et al., Monitoring Respiratory Rate Based on Tracheal Sounds. First Experieances, Proceedings of the 26th Annual Int'l Conf. of the IEEE EMBS (Sep. 2004), 317-320.
Watt, R. C.; "Alarms and Anesthesia. Challenges in the design of Intelligent systems for Patient Monitoring"; IEEE Engineering in Medicine and biology; Dec. 1993, p. 34-41.
Welch Allyn, ECG ASIC, Product Data Sheete, 2001.
Supplementary Partial European Search Report for International Application No. 05732095.4, dated Jun. 26, 2009 in 4 pages.
Theimer et al., "Definitions of audio features for music content description", Algorithm Engineering Report TR08-2-001, Feb. 2008.
Stewart, C., Larson, V., "Detection and classification of acoustic signals from fixed-wing aircraft," Systems Engineering, CH3051-0/91/0000-0025, IEEE, 1991.
Johnston, Development of a Signal Processing Library for Extraction of Sp02, HR, HRV, and RR from Photoplethysmographic Waveforms, Thesis: Degree of Master of Science, Worcester Polytechnic Institute, date of presentation/defense Jul. 17, 2006, date listed Jul. 27, 2006.

* cited by examiner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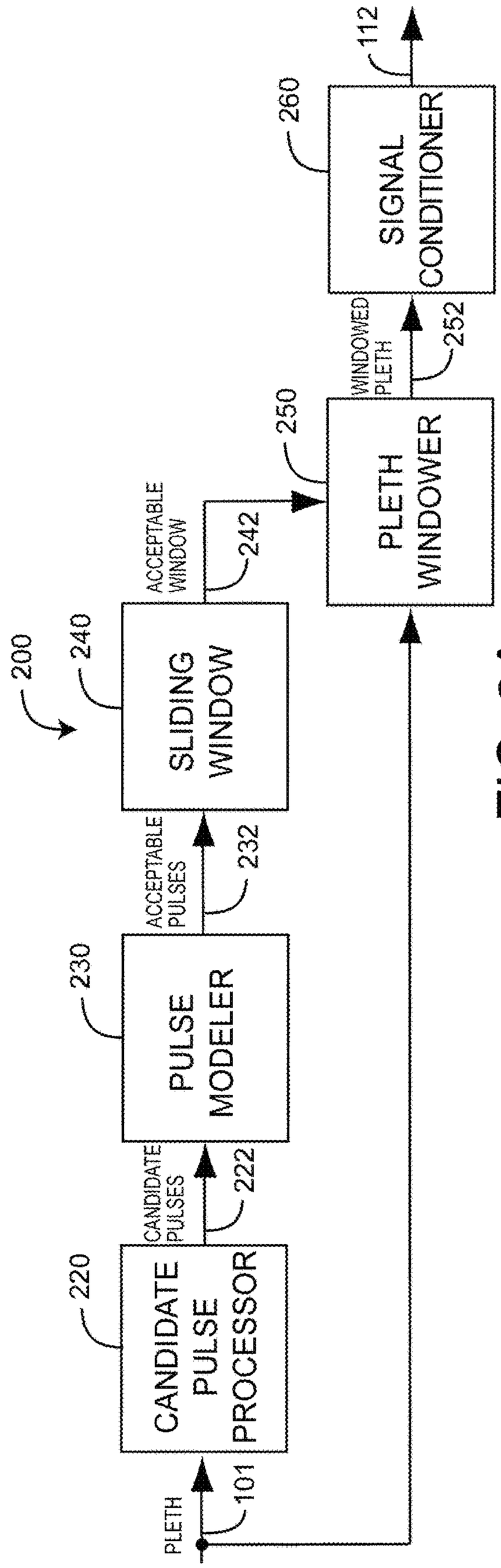
RR
104
130
POST-PROCESSOR
102
123
125
127
122
PLETH PROCESSOR 1
124
PLETH PROCESSOR 2
126
PLETH PROCESSOR N
120
112
200
PRE-PROCESSOR
101
PLETH

FIG. 1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220
CANDIDATE PULSES
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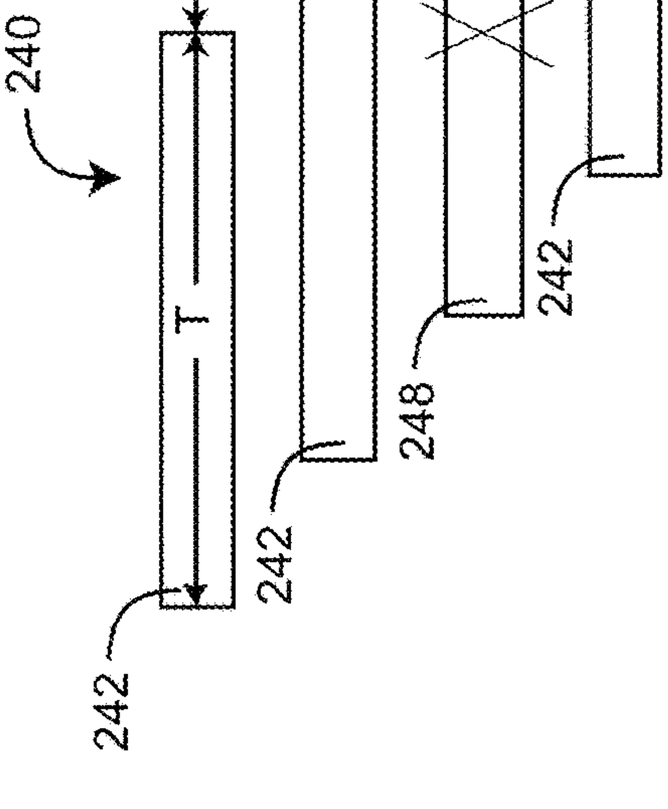
ACCEPTABLE PULSES
232
SLIDING WINDOW
240
ACCEPTABLE WINDOW
242
PLETH WINDOWER
250
WINDOWED PLETH
252
SIGNAL CONDITIONER
260
112
200

FIG. 2A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242
T
Δt
244
242
248
242

FIG. 2B

FIG. 3A

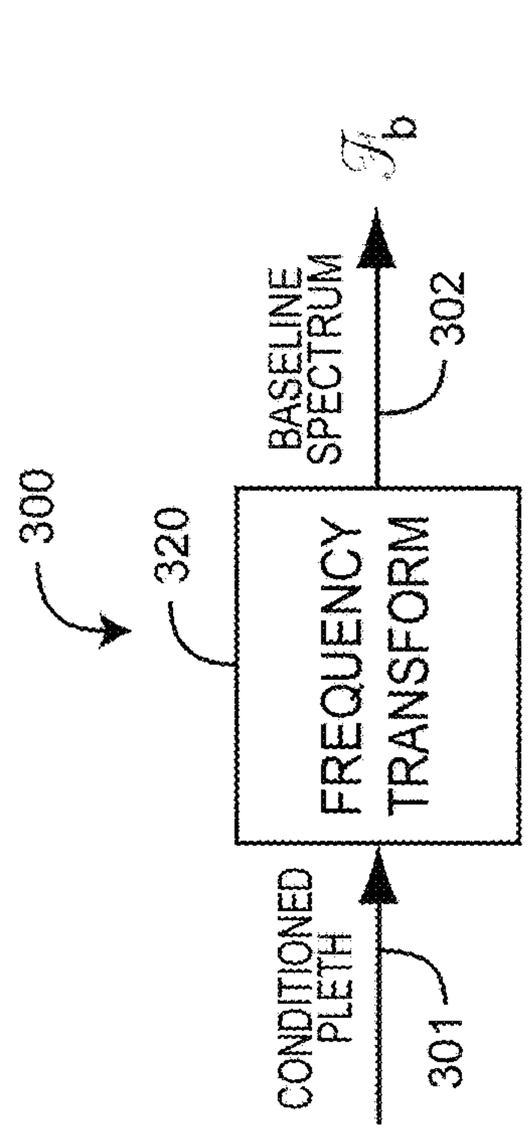


FIG. 3B

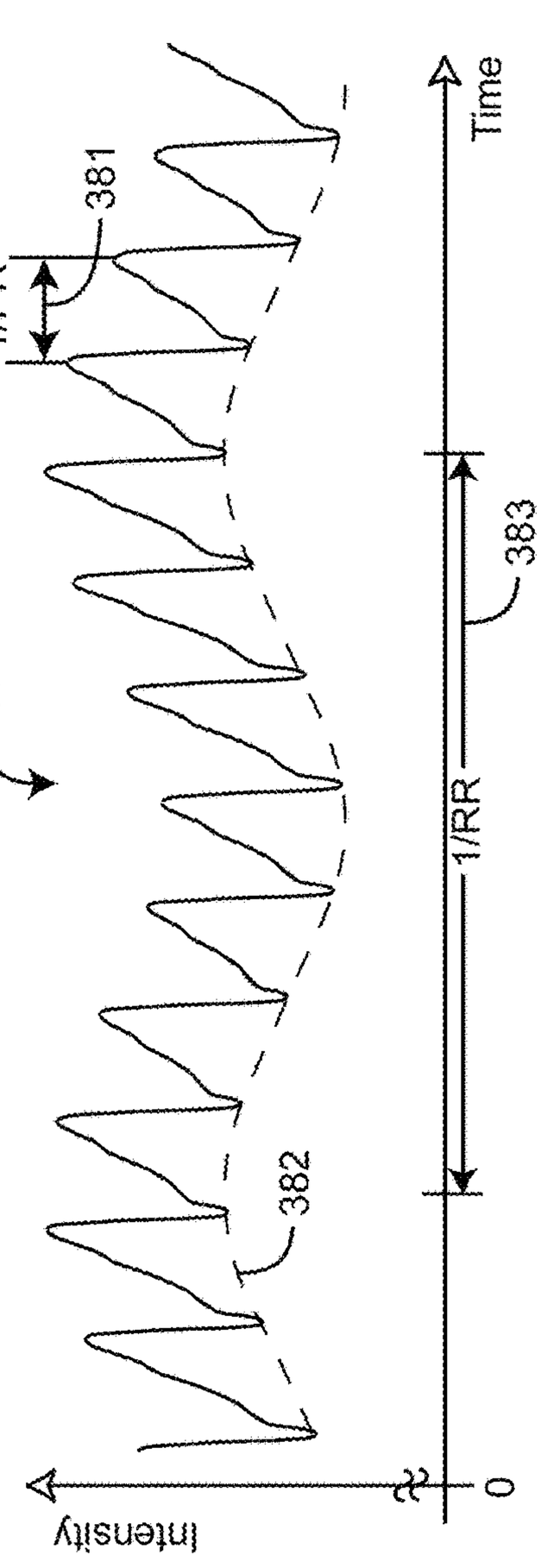


FIG. 3C

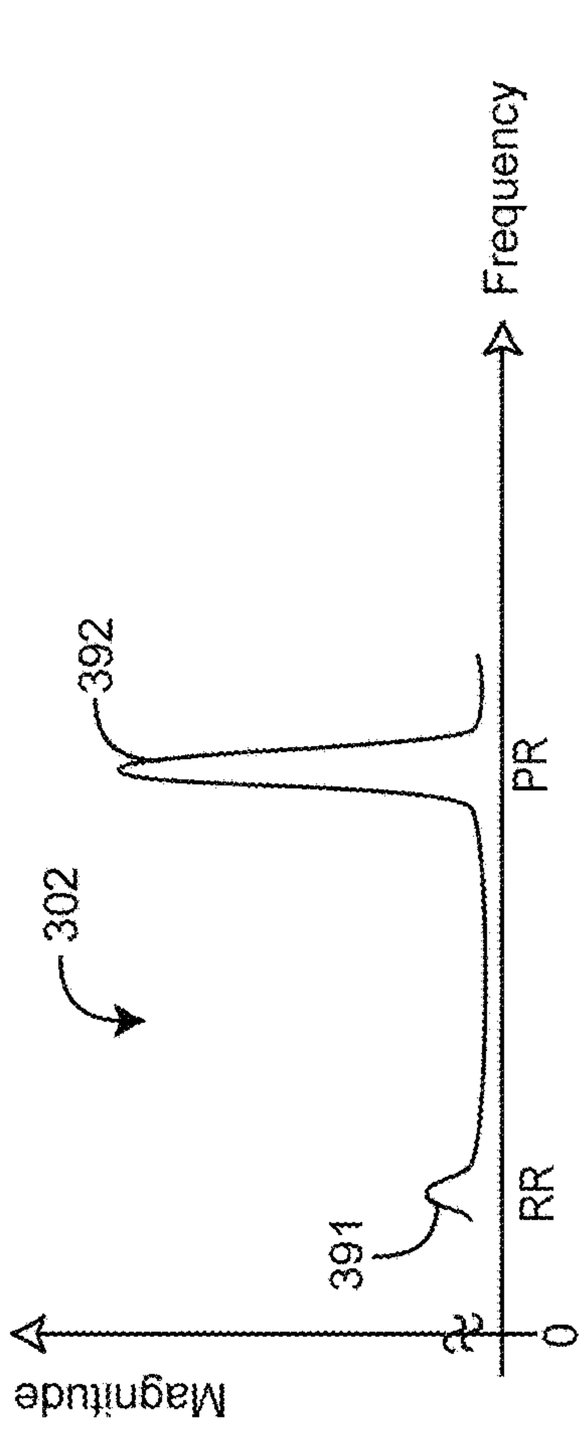


FIG. 4A

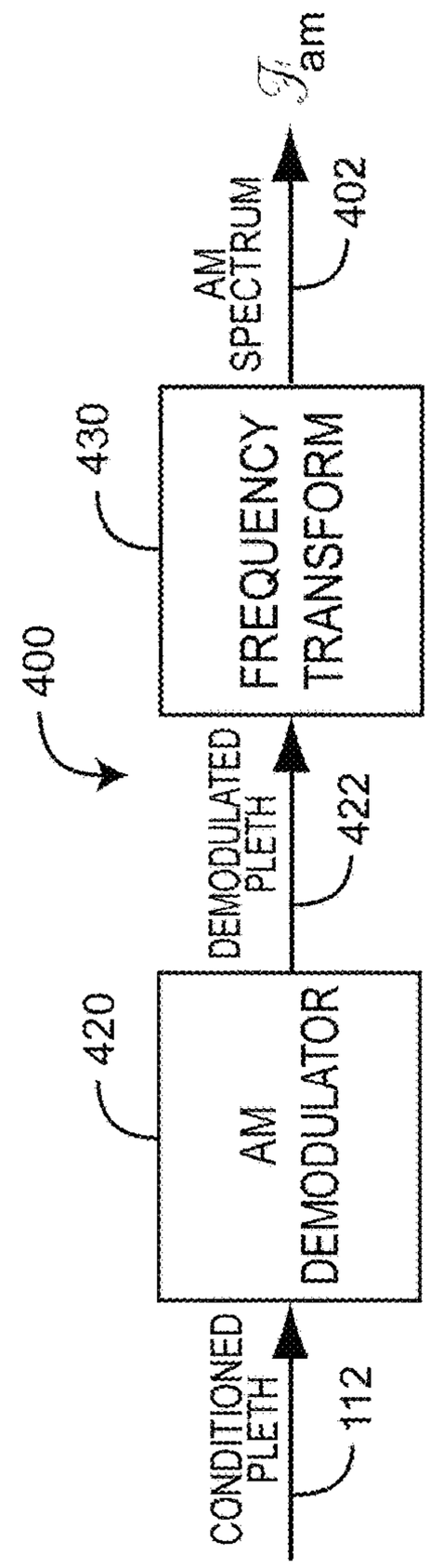


FIG. 4B

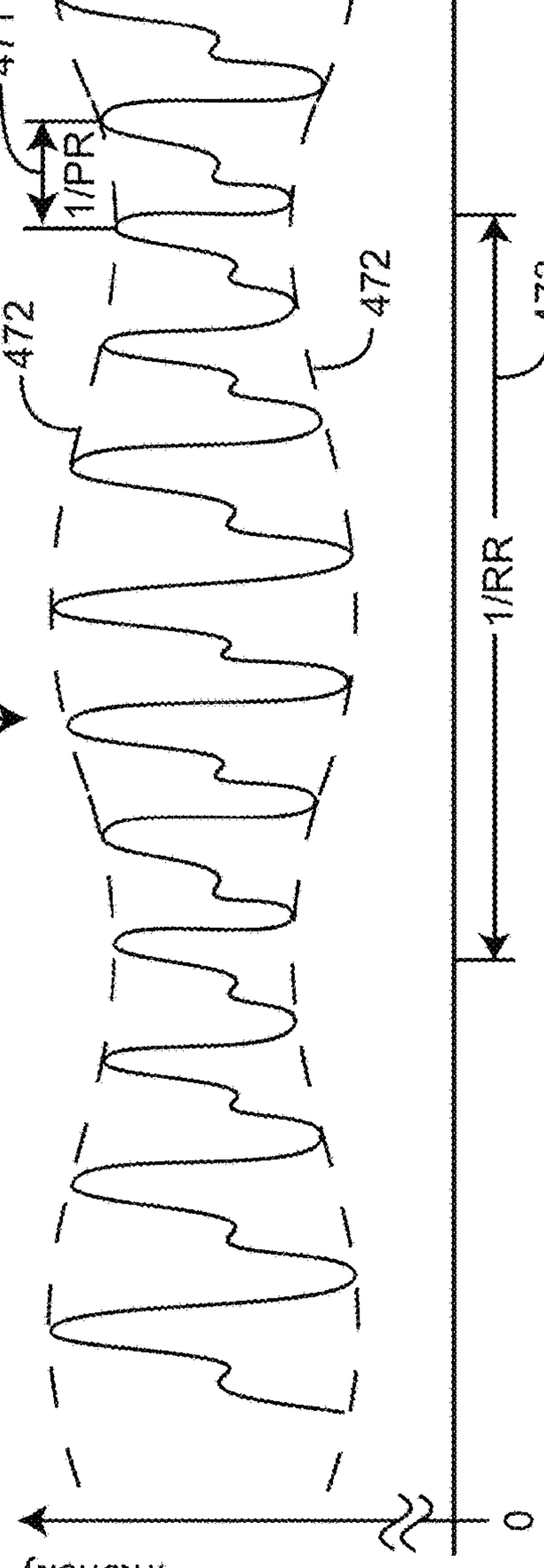


FIG. 4D

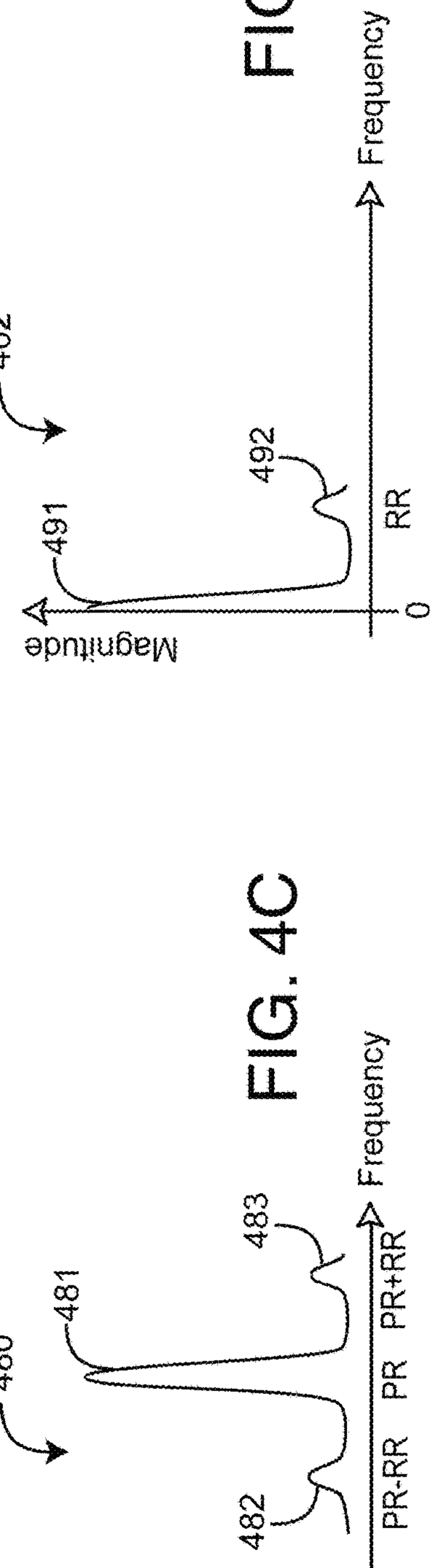


FIG. 4C

FIG. 5A

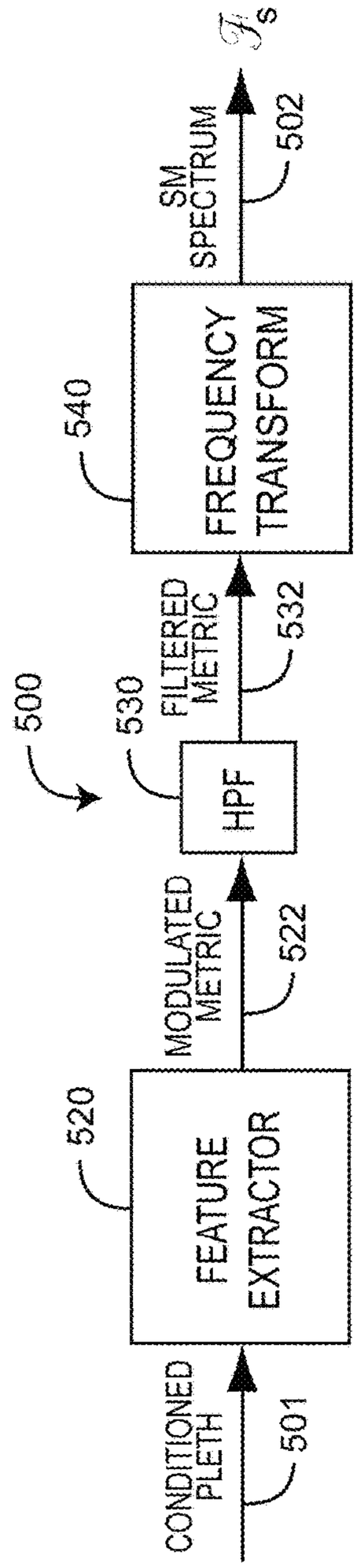


FIG. 5B

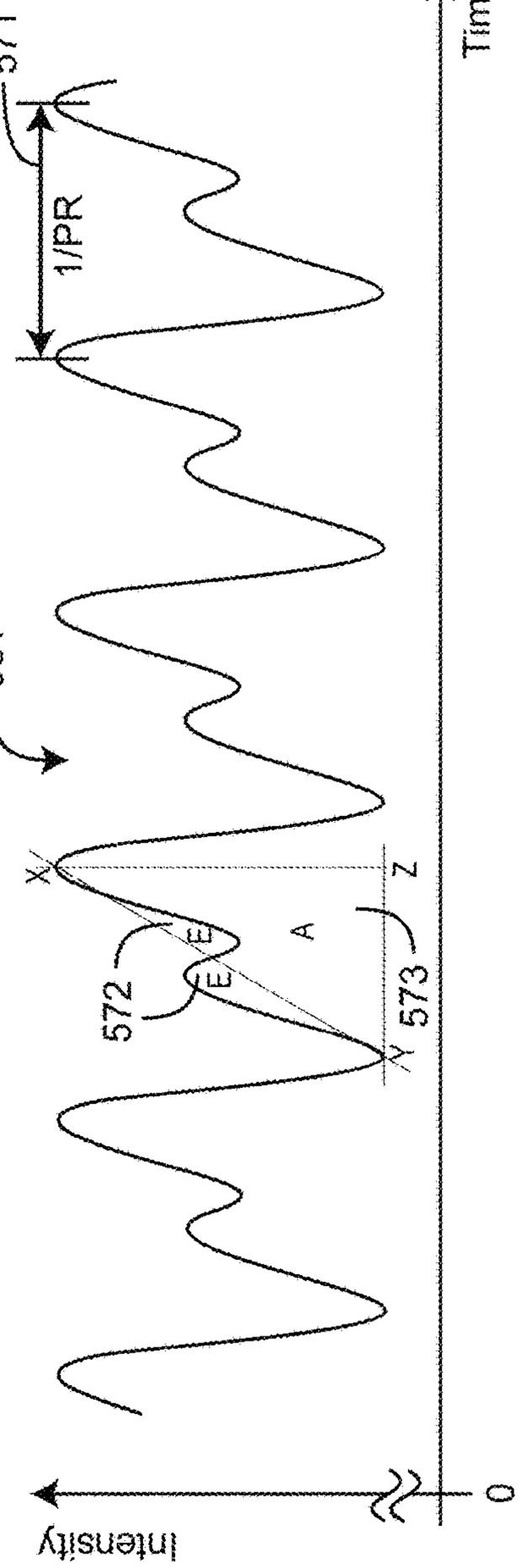


FIG. 5D

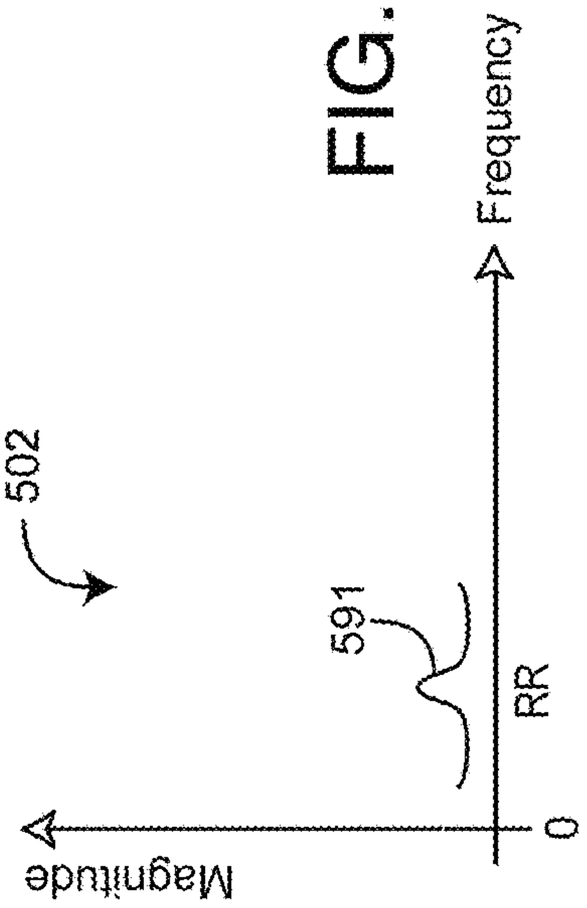
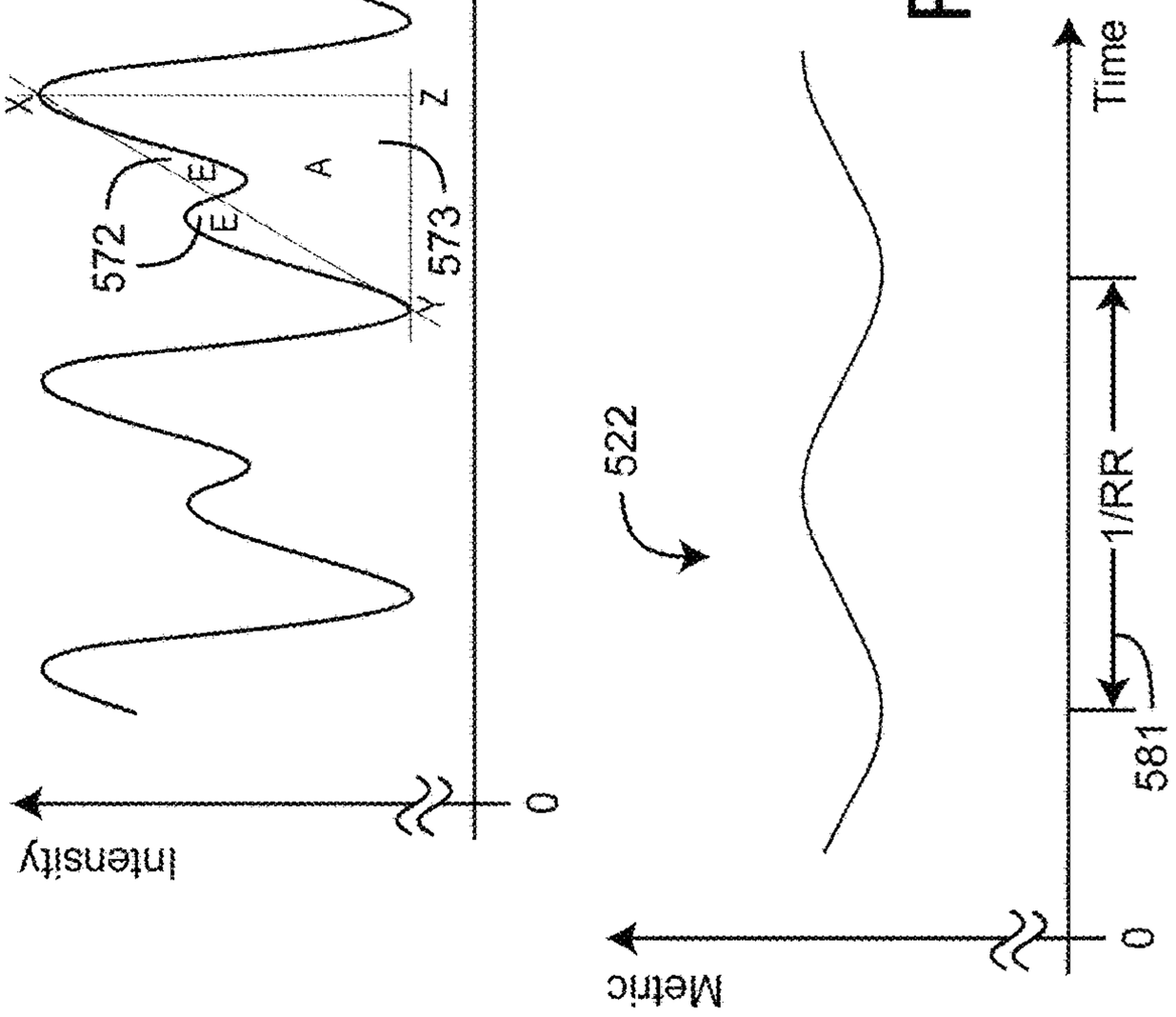


FIG. 5C



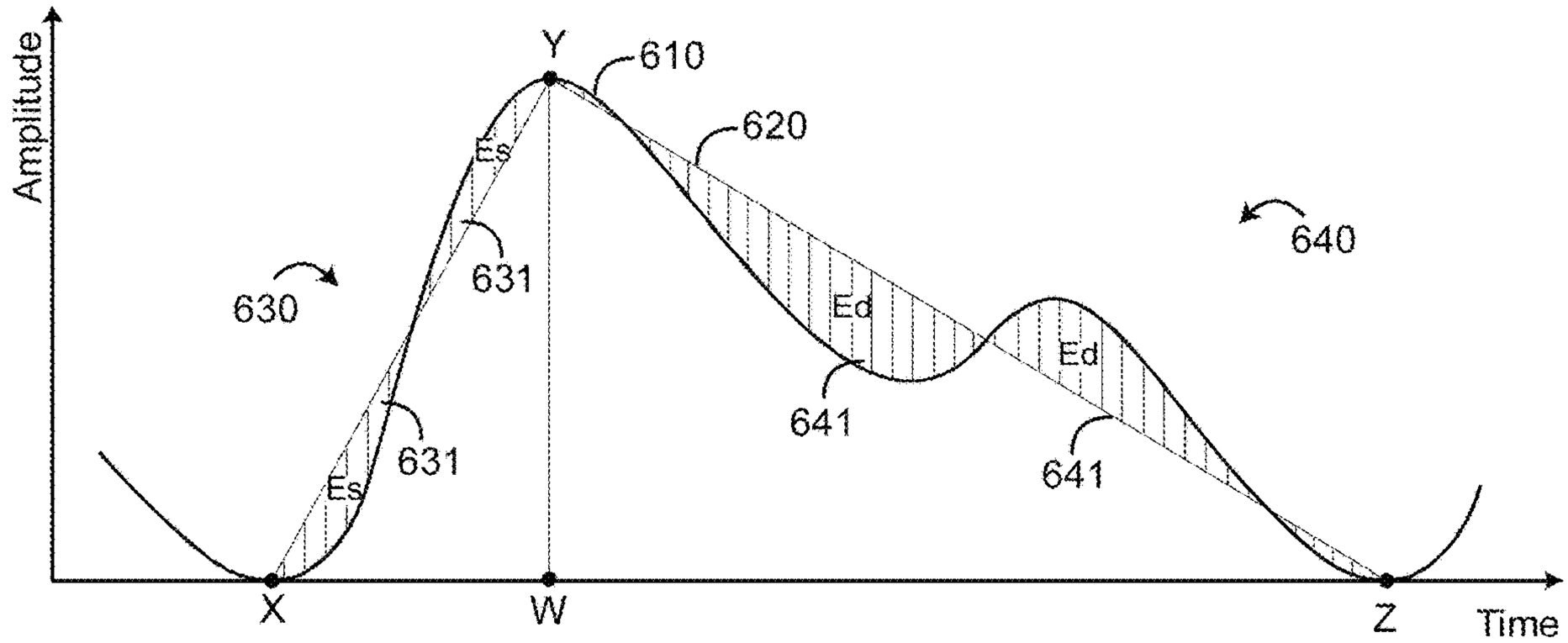

Amplitude
Y
610
620
Es
631
630
640
Ed
641
Es
631
641
X
W
Z
Time

FIG. 6A

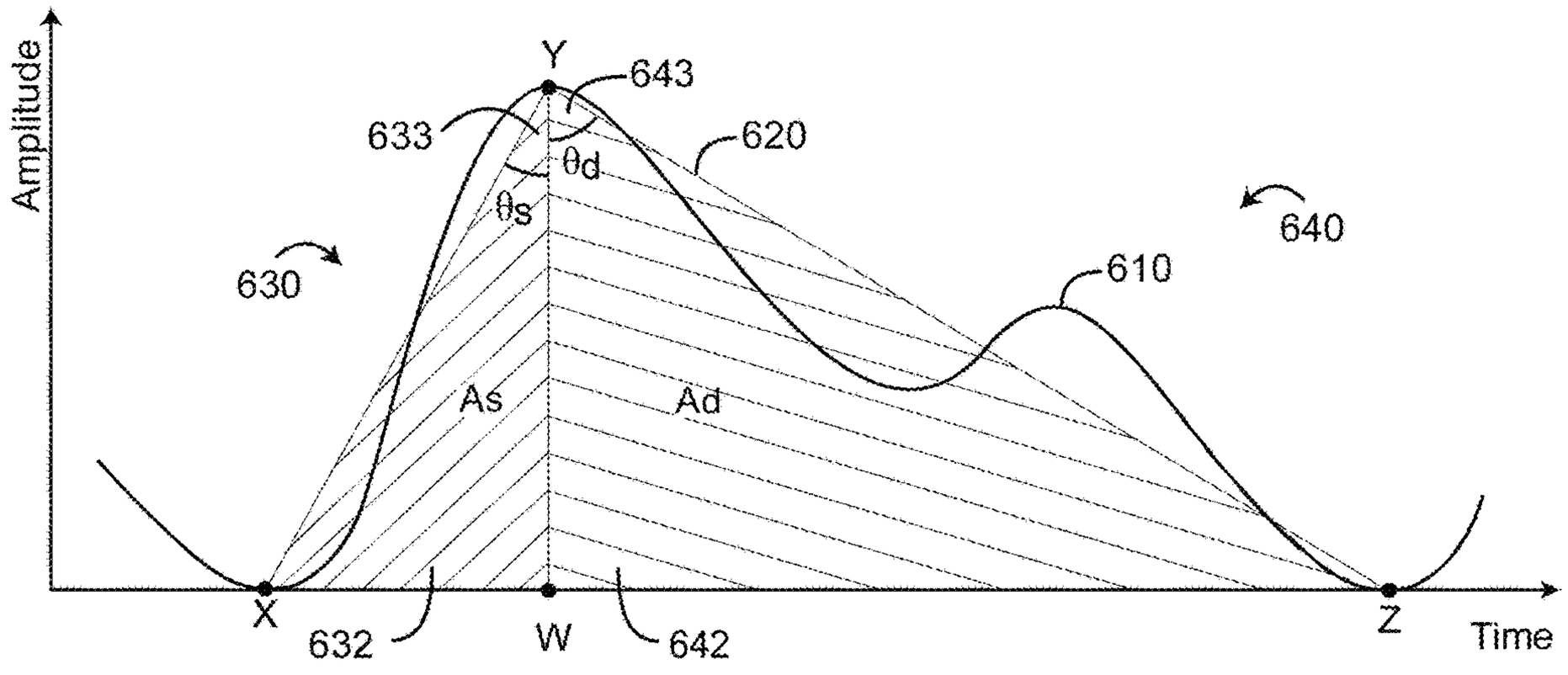

Amplitude
Y
643
633
620
θd
θs
630
640
610
As
Ad
X
632
W
642
Z
Time

FIG. 6B

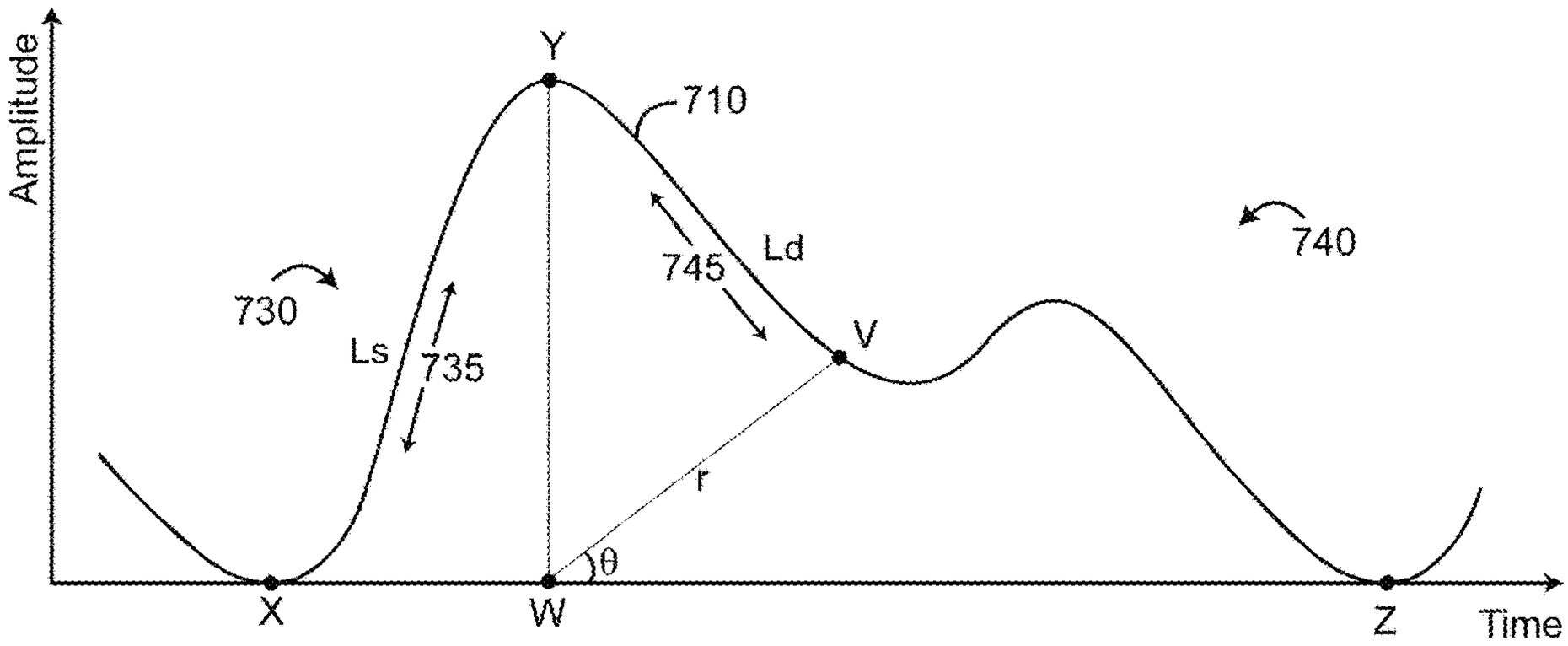

Amplitude
Y
710
730
Ls
735
745
Ld
740
V
r
θ
X
W
Z
Time

FIG. 7A

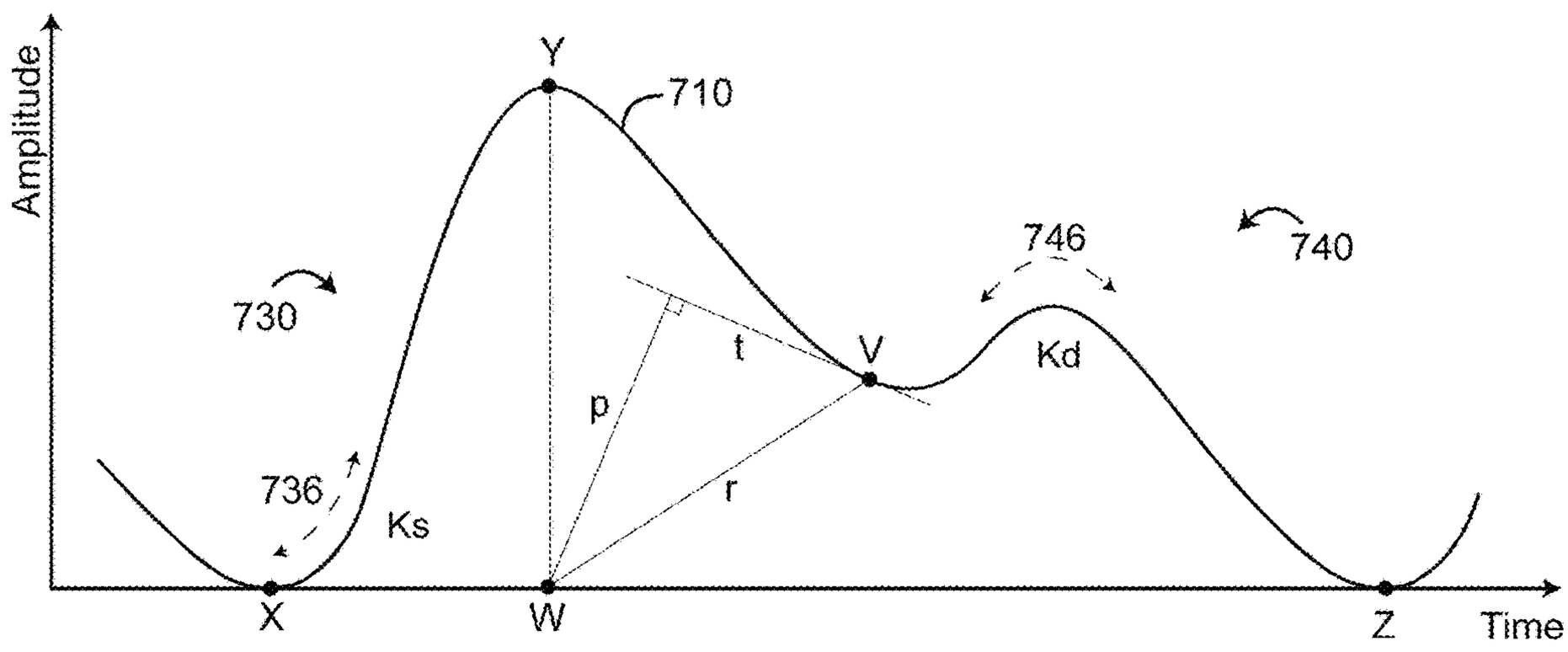

Amplitude
Y
710
730
746
740
t
V
Kd
p
736
r
Ks
X
W
Z
Time

FIG. 7B

FIG. 8A

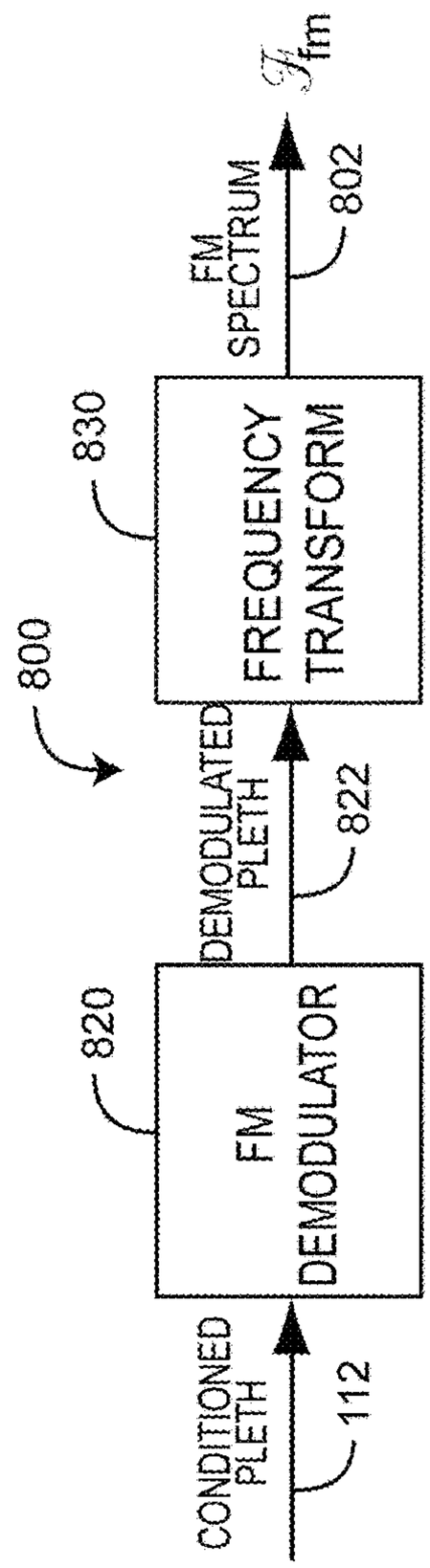


FIG. 8B

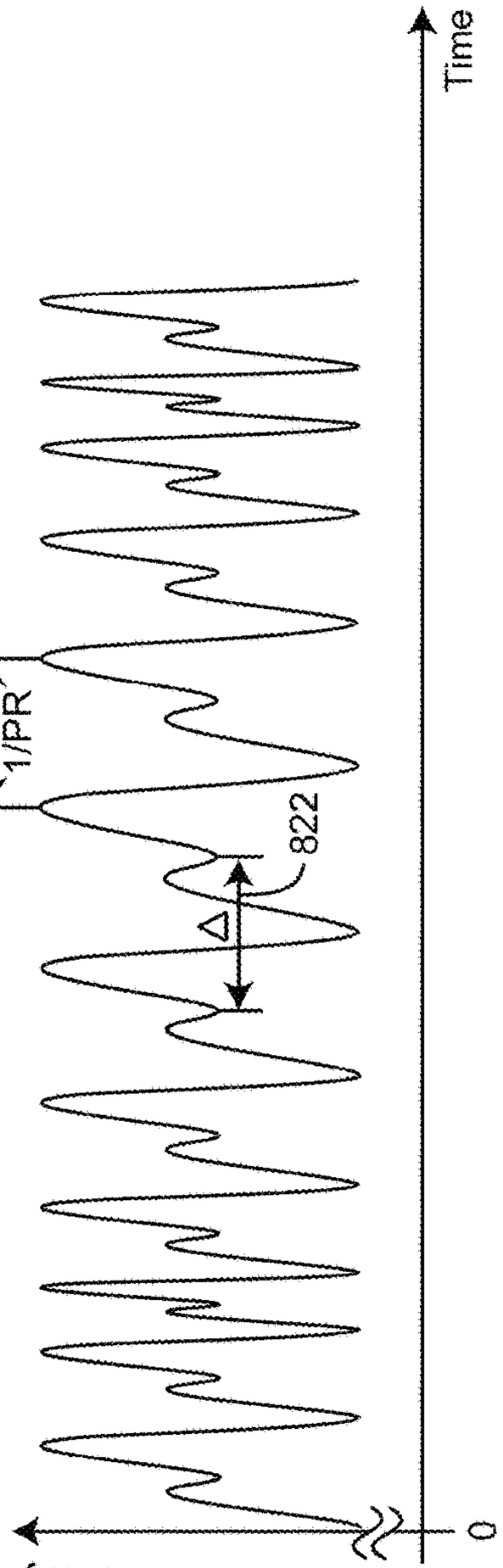


FIG. 8D

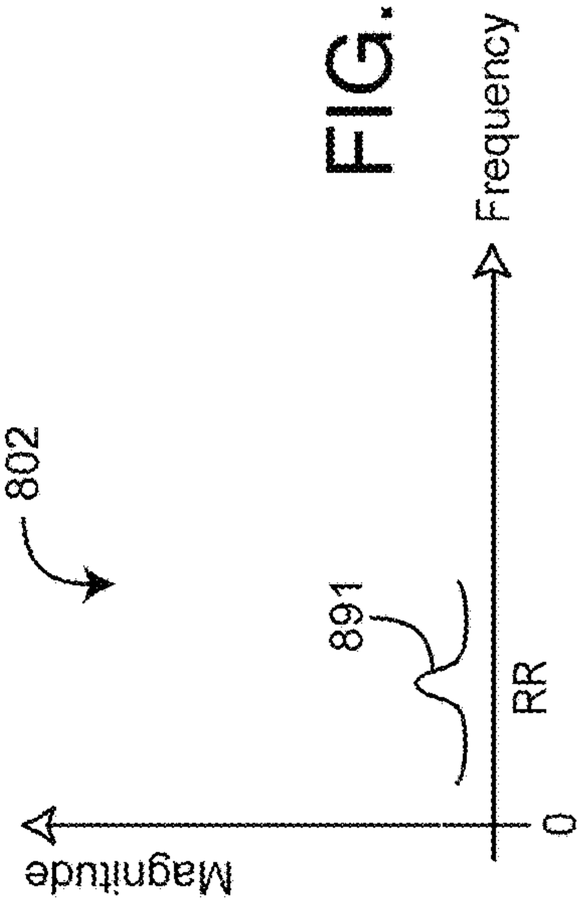
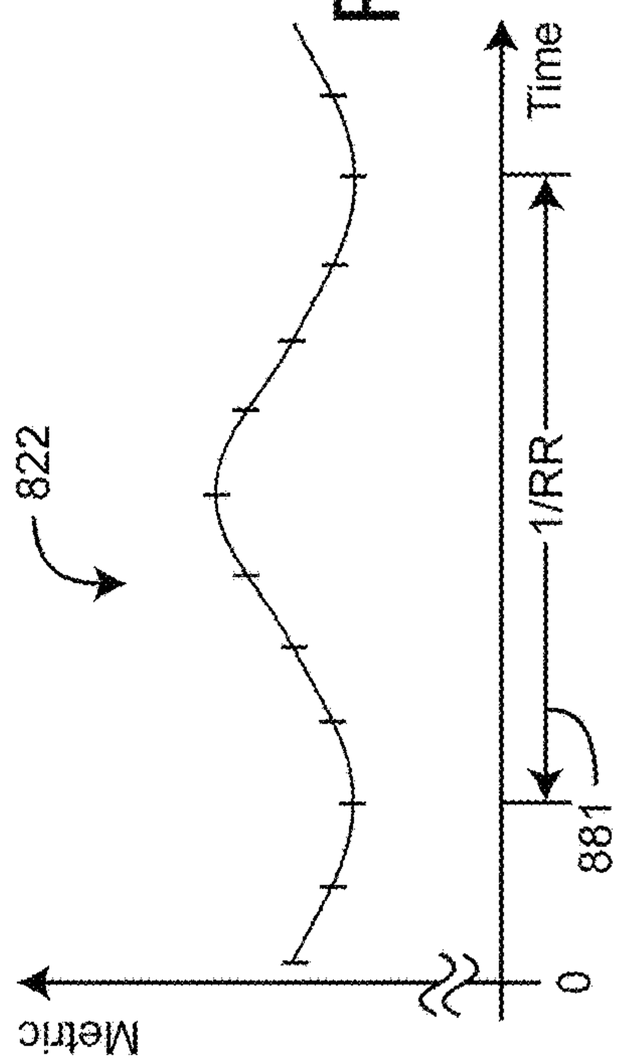


FIG. 8C



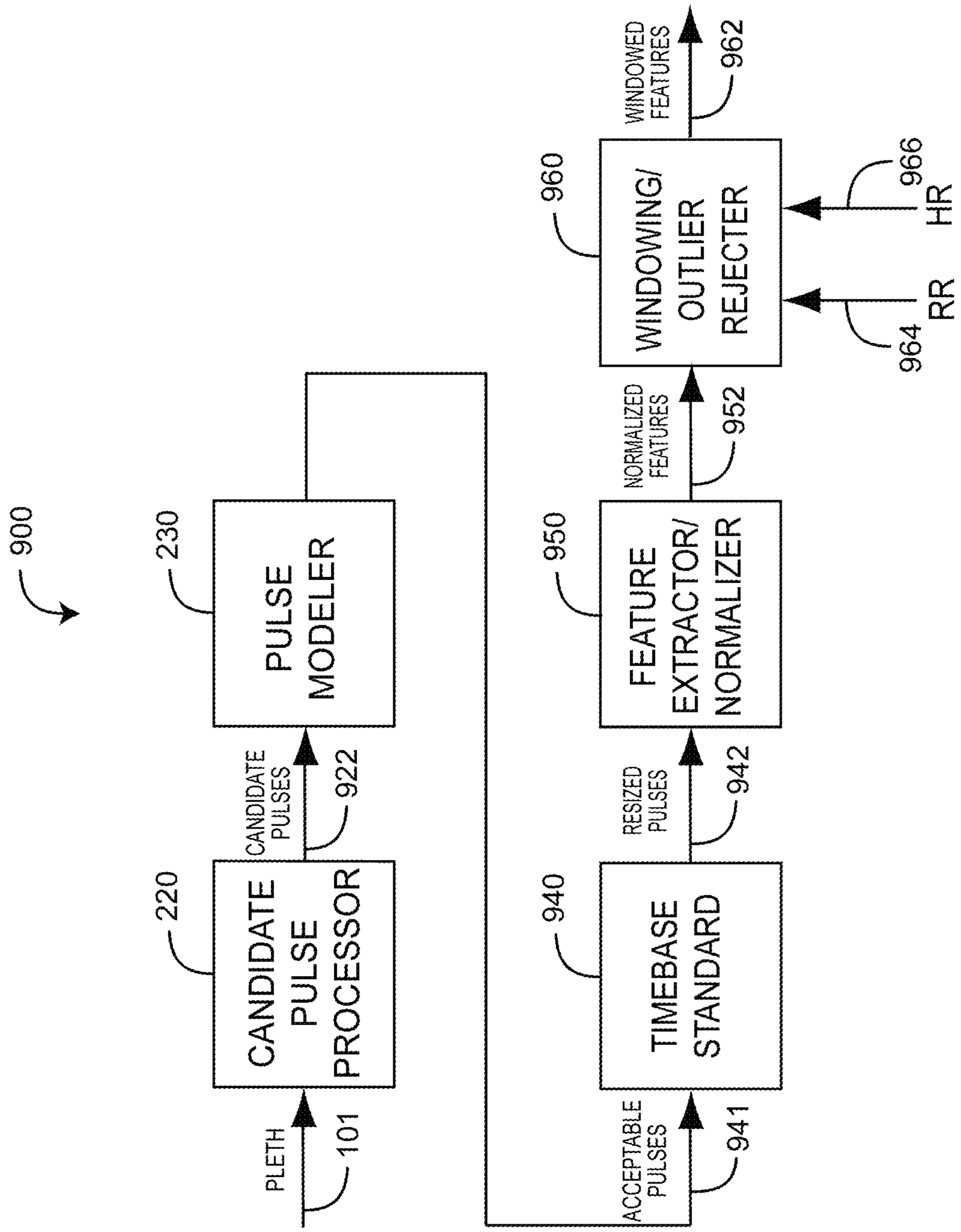

900
230
PULSE MODELER
CANDIDATE PULSES
922
220
CANDIDATE PULSE PROCESSOR
PLETH
101
960
WINDOWED FEATURES
962
966
HR
RR
964
950
FEATURE EXTRACTOR/ NORMALIZER
NORMALIZED FEATURES
952
RESIZED PULSES
942
940
TIMEBASE STANDARD
ACCEPTABLE PULSES
941

FIG. 9

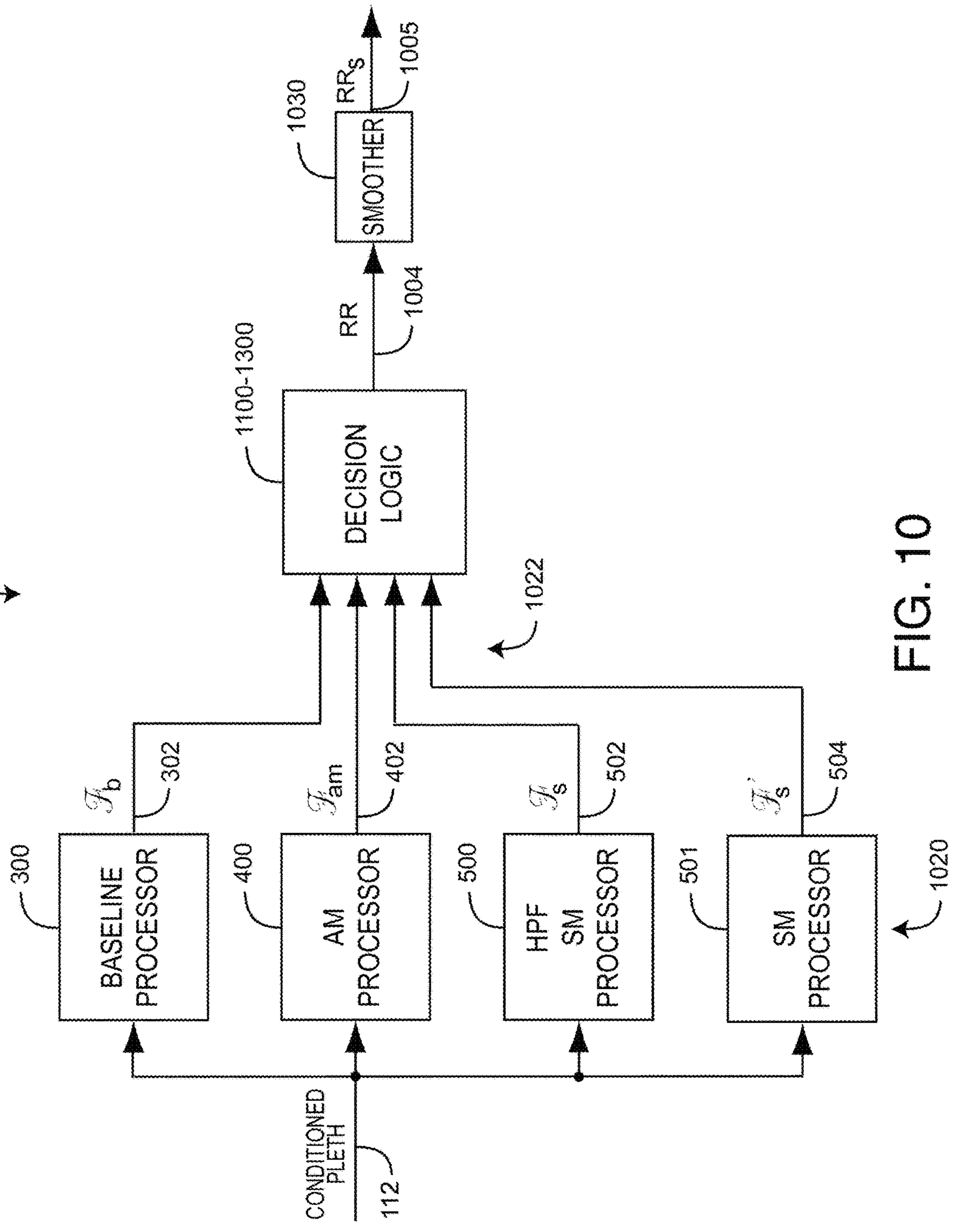

1000
CONDITIONED PLETH
112
BASELINE PROCESSOR
300
$\mathscr{F}_b$
302
AM PROCESSOR
400
$\mathscr{F}_{am}$
402
HPF SM PROCESSOR
500
$\mathscr{F}_s$
502
SM PROCESSOR
501
$\mathscr{F}_s'$
504
1020
1022
DECISION LOGIC
1100-1300
RR
1004
SMOOTHER
1030
RR_S
1005

FIG. 10

FIG. 11A

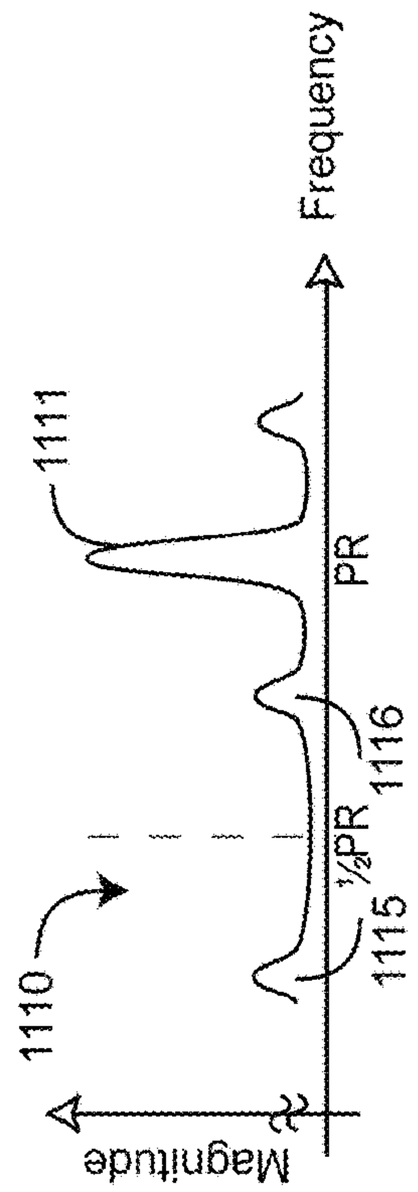


FIG. 11B

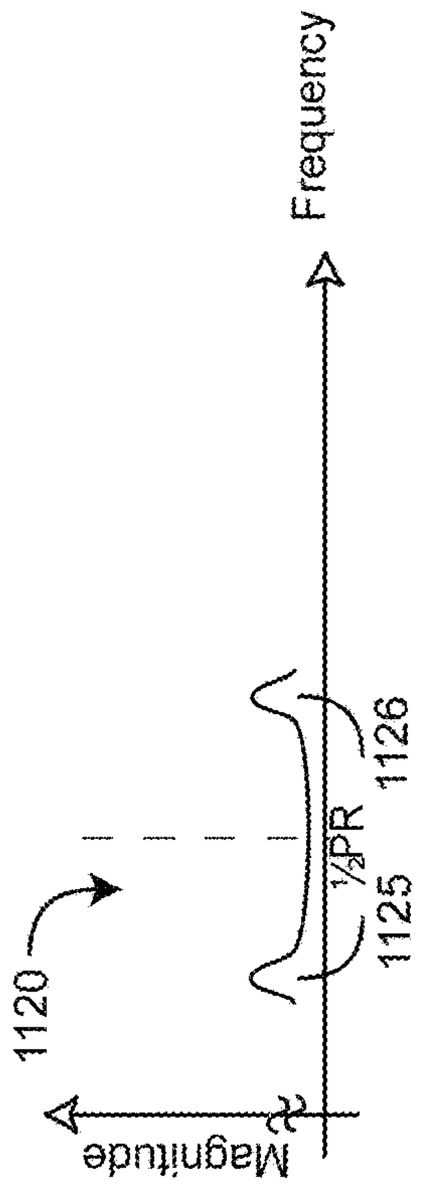


FIG. 11C

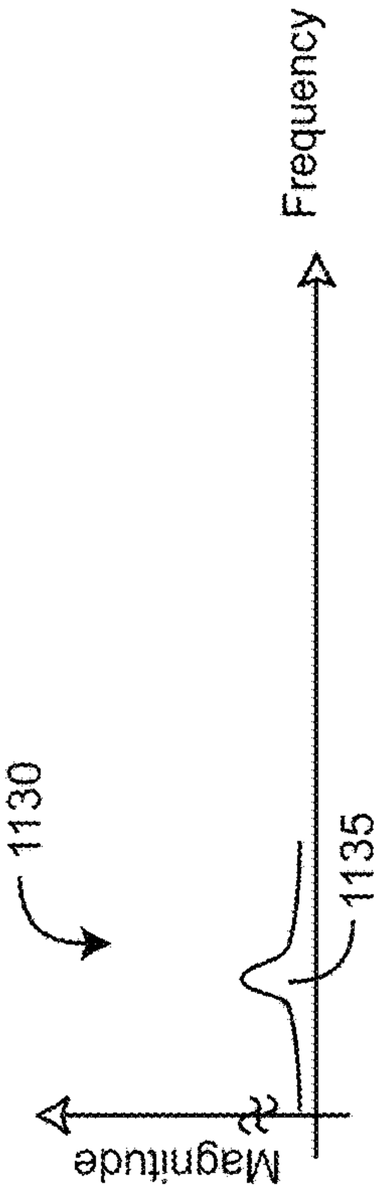
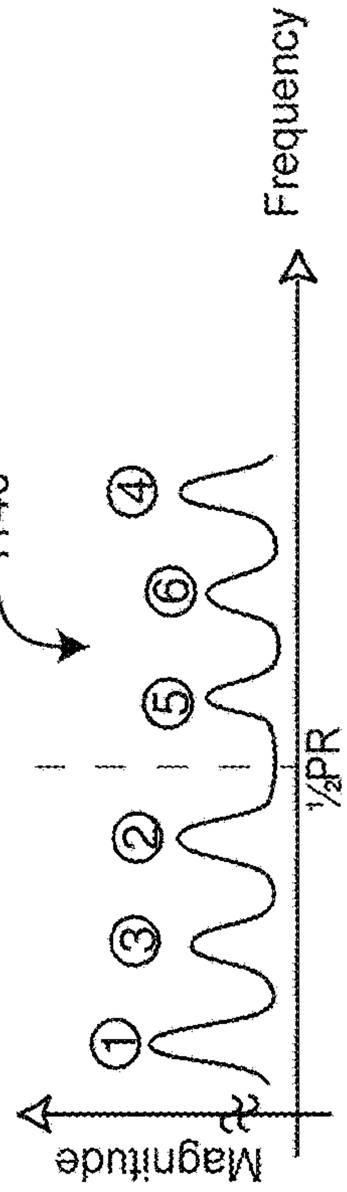


FIG. 11D



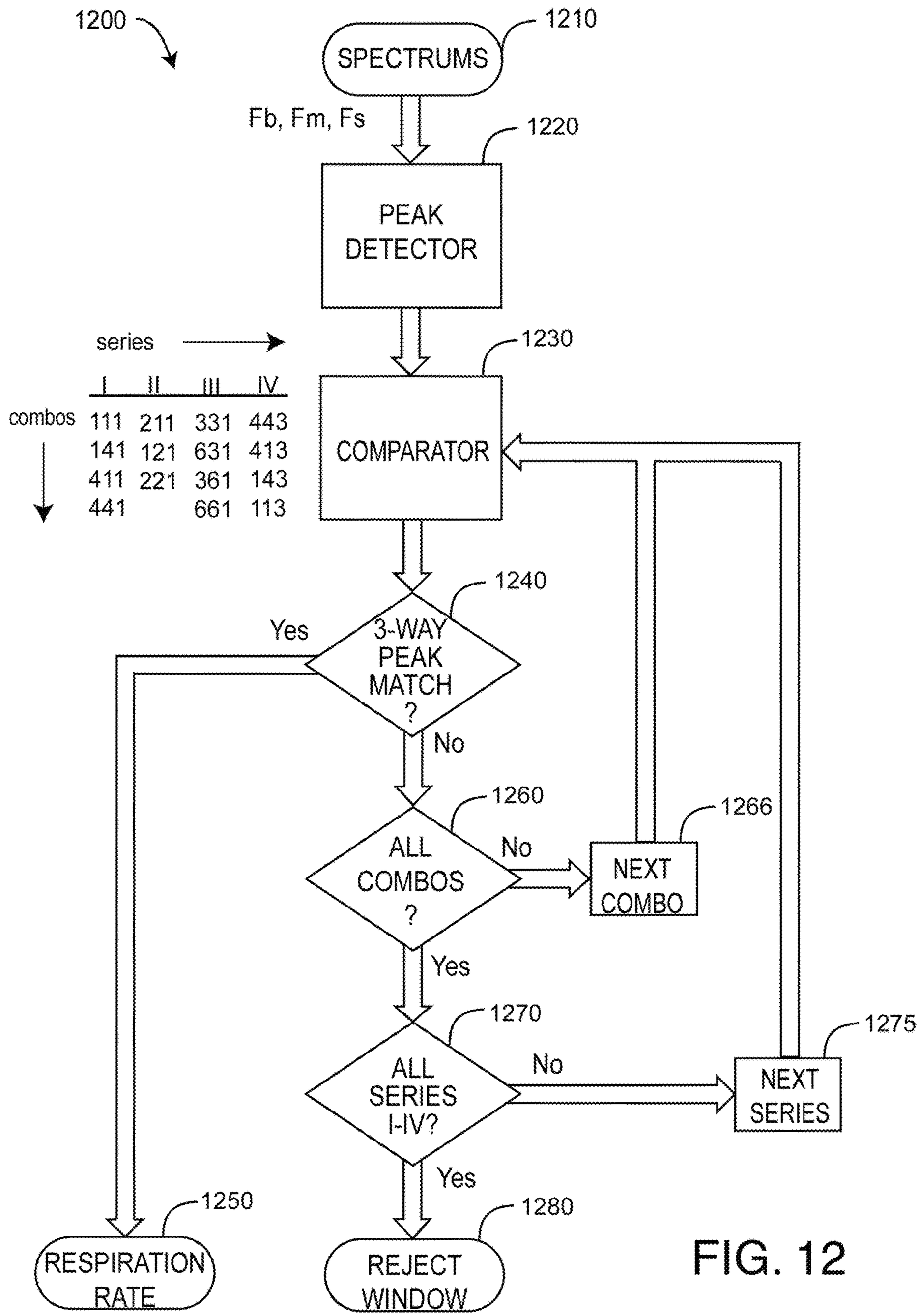

1200
SPECTRUMS
1210
Fb, Fm, Fs
1220
PEAK DETECTOR
series
I II III IV
combos
111 211 331 443
141 121 631 413
411 221 361 143
441 661 113
1230
COMPARATOR
1240
3-WAY PEAK MATCH ?
Yes
No
1260
ALL COMBOS ?
No
1266
NEXT COMBO
Yes
1270
ALL SERIES I-IV?
No
1275
NEXT SERIES
Yes
1250
RESPIRATION RATE
1280
REJECT WINDOW

FIG. 12

V	VI
1_1	11_
_11	⋮
	16_
	21_
	⋮
	26_
	31
	⋮
	66_

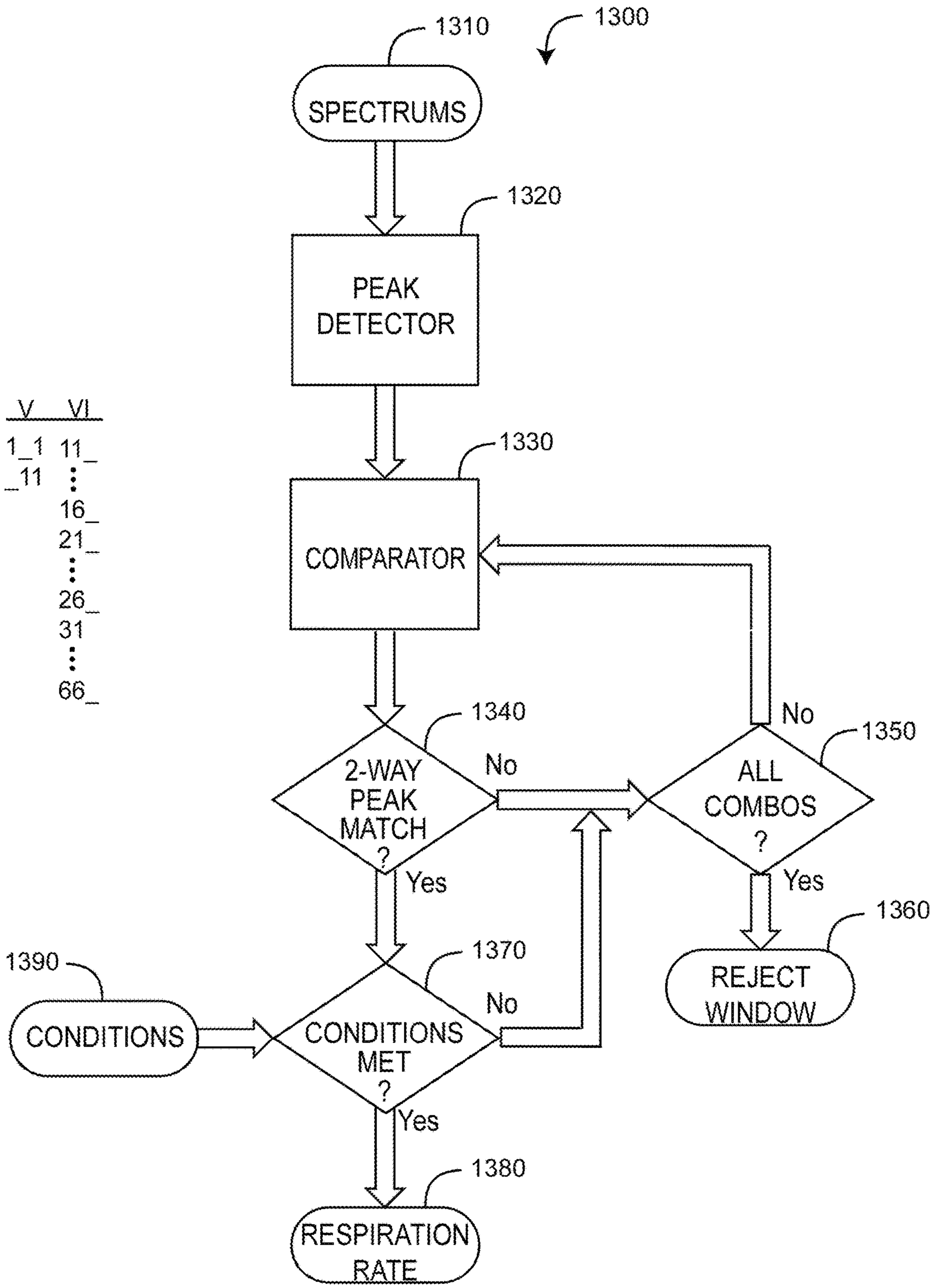


FIG. 13

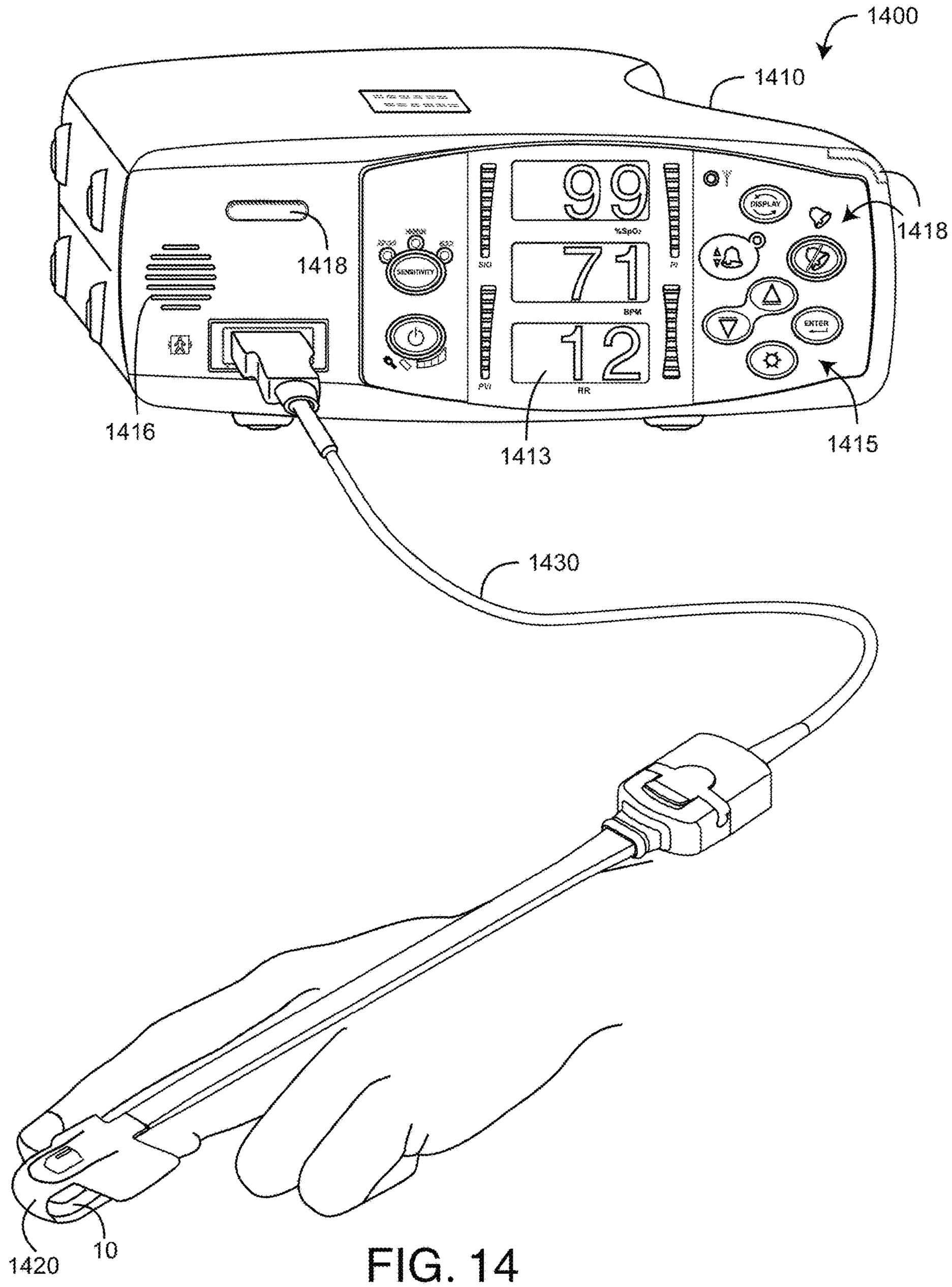

1400
1410
1418
1418
1416
1413
1415
1430
1420
10
99
%SpO2
71
BPM
12
RR
SIG
PVI
SENSITIVITY
DISPLAY
ENTER

FIG. 14

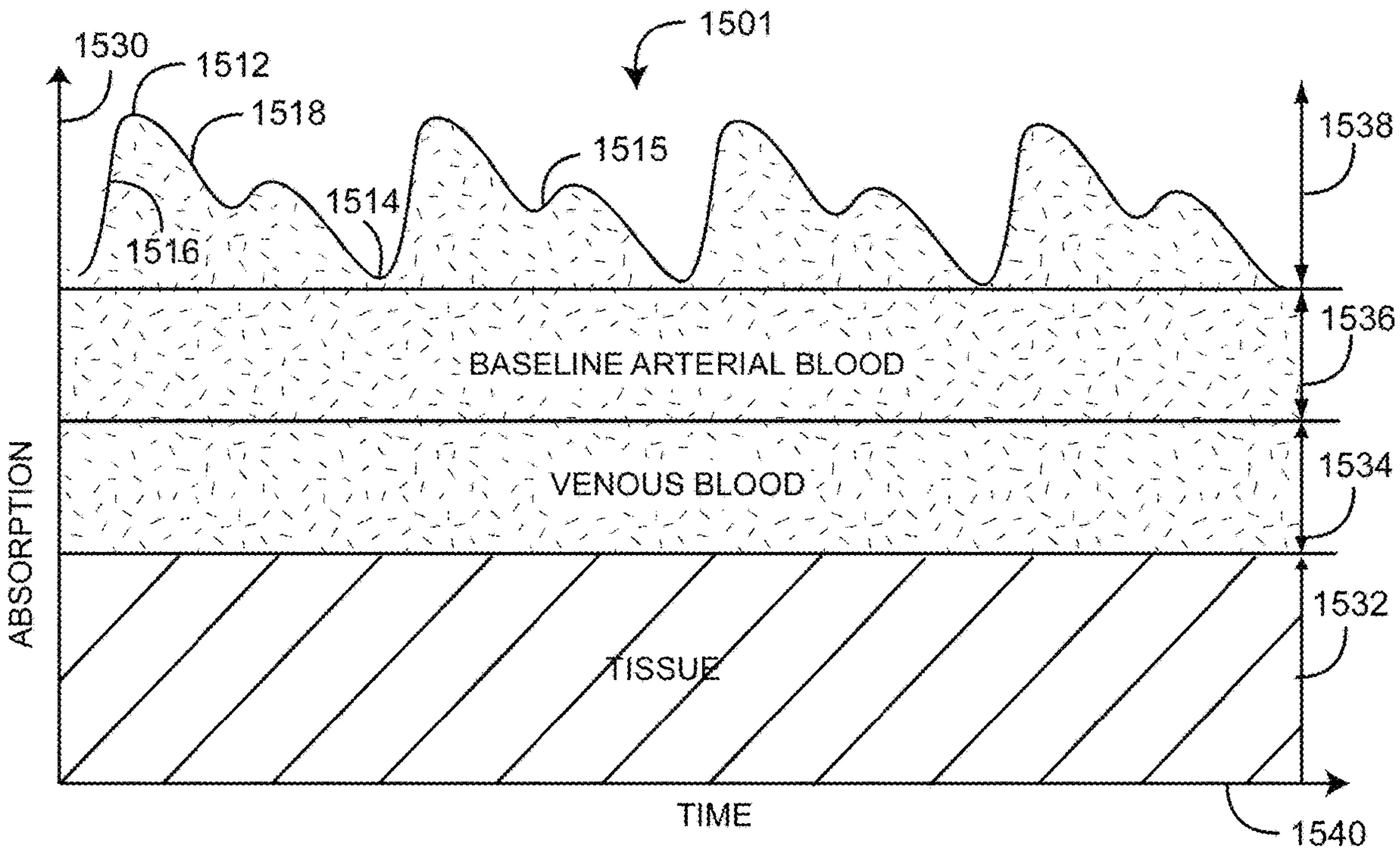


FIG. 15A

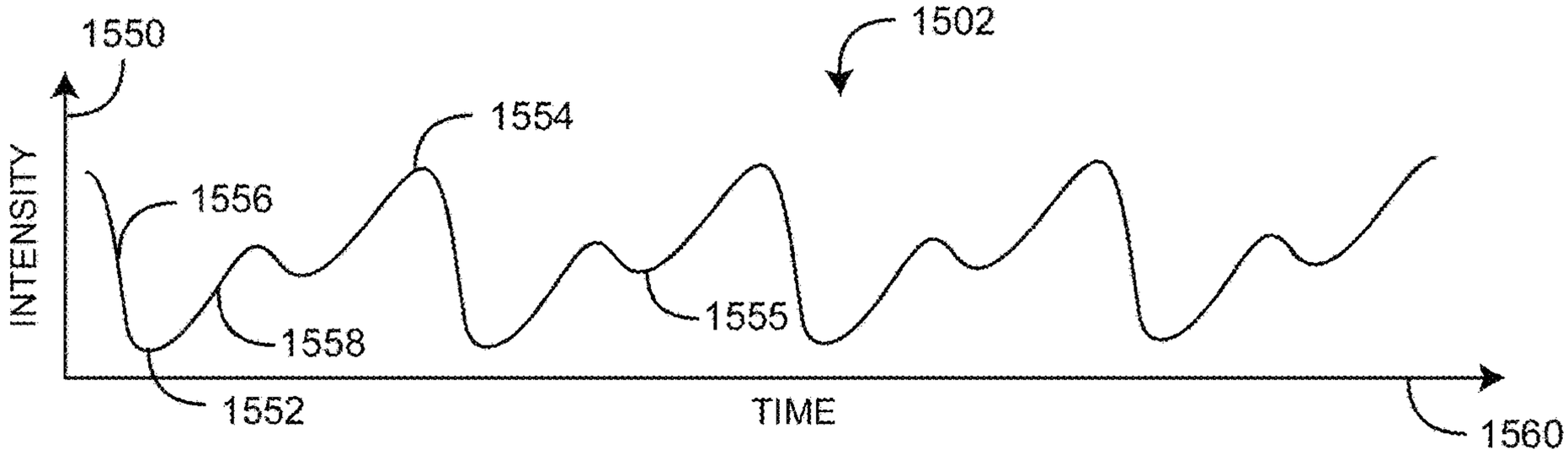


FIG. 15B

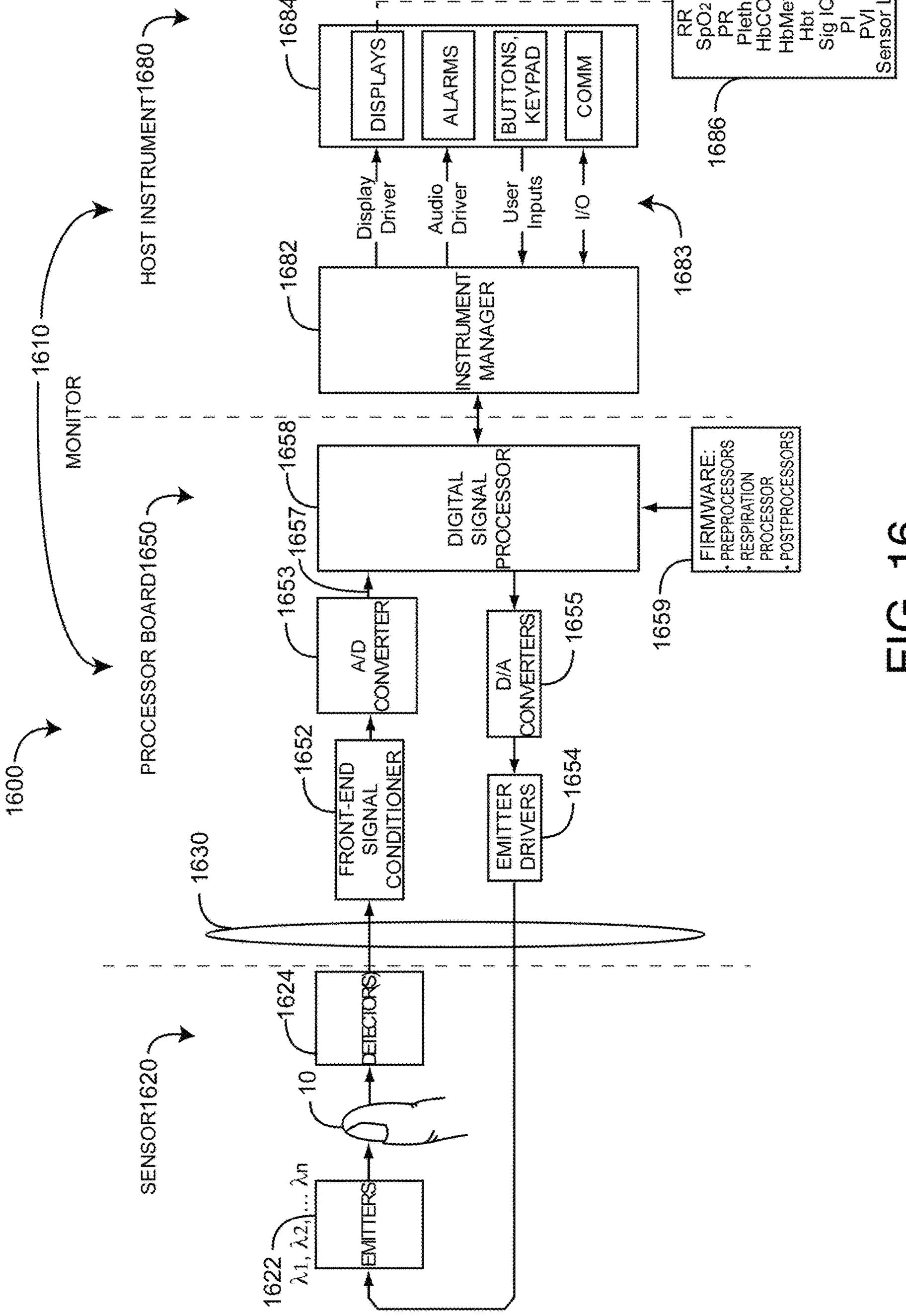

1600
1610
MONITOR
HOST INSTRUMENT1680
PROCESSOR BOARD1650
1630
SENSOR1620
1622
λ1, λ2, ... λn
EMITTERS
1624
DETECTORS
10
1652
FRONT-END SIGNAL CONDITIONER
1653
A/D CONVERTER
1654
EMITTER DRIVERS
1655
D/A CONVERTERS
1657
DIGITAL SIGNAL PROCESSOR
1658
1659
FIRMWARE:
• PREPROCESSORS
• RESPIRATION PROCESSOR
• POSTPROCESSORS
1682
INSTRUMENT MANAGER
1683
Display Driver
Audio Driver
User Inputs
I/O
1684
DISPLAYS
ALARMS
BUTTONS, KEYPAD
COMM
1686
RR
SpO2
PR
Pleth
HbCO
HbMet
Hbt
Sig IQ
PI
PVI
Sensor Life

FIG. 16

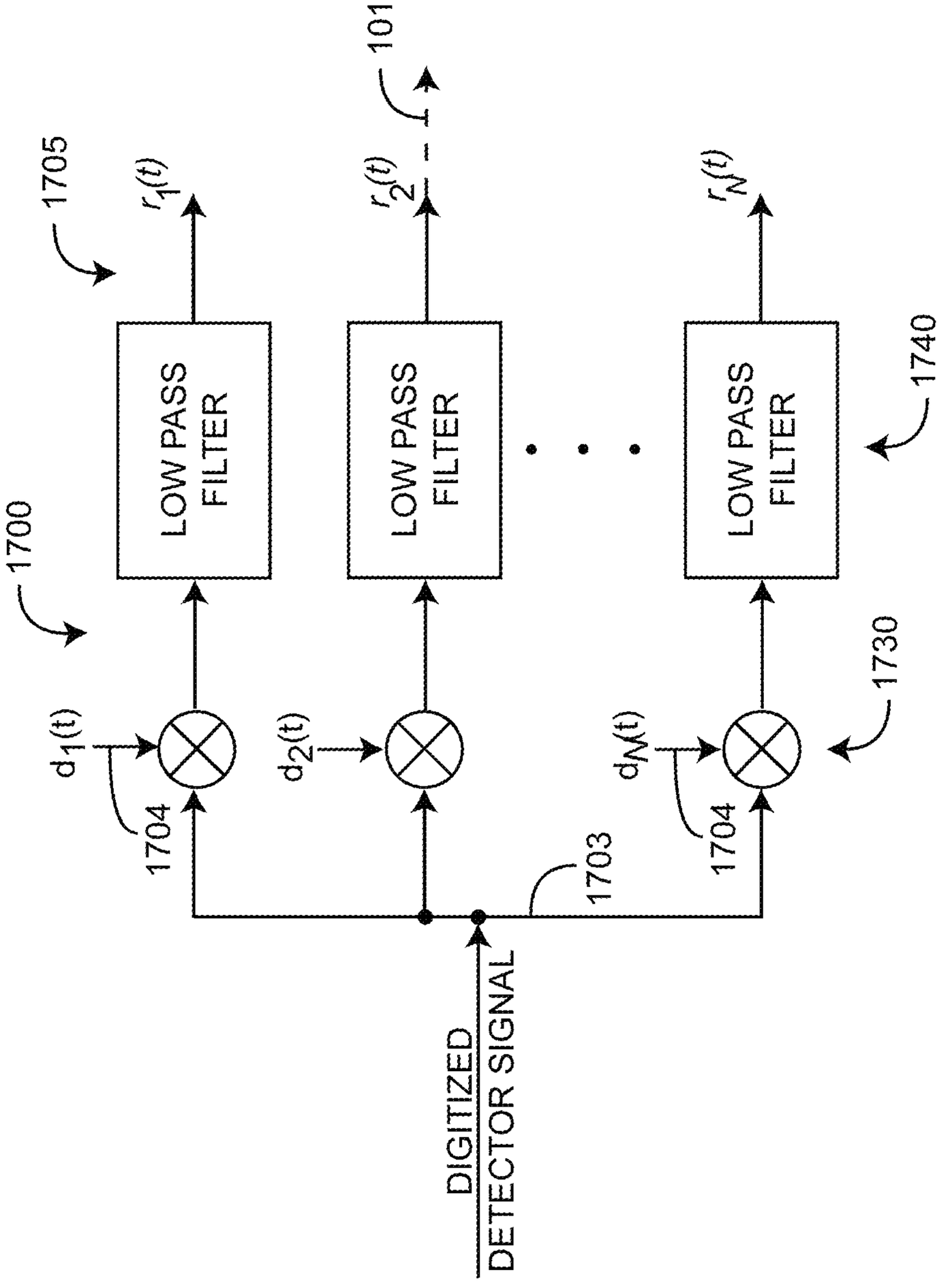

101
1705
$r_1(t)$
$r_2(t)$
$r_N(t)$
LOW PASS FILTER
LOW PASS FILTER
LOW PASS FILTER
1740
1700
$d_1(t)$
$d_2(t)$
$d_M(t)$
1730
1704
1703
1704
DIGITIZED DETECTOR SIGNAL

FIG. 17

PLETHYSMOGRAPHIC RESPIRATION RATE DETECTION

PRIORITY CLAIM TO RELATED PROVISIONAL APPLICATIONS

The present application is a continuation of U.S. patent application Ser. No. 15/095,912, filed Apr. 11, 2016, titled Plethysmographic Respiration Rate Detection, which is a divisional of U.S. patent application Ser. No. 13/076,423, filed Mar. 30, 2011, titled Plethysmographic Respiration Processor, which claims priority benefit under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application No. 61/319,256, filed Mar. 30, 2010, titled Plethysmographic Respiration Processor and U.S. Provisional Patent Application No. 61/364,141, filed Jul. 14, 2010, titled Plethysmographic Respiration Detector; all of the above-cited patent applications are hereby incorporated by reference herein.

BACKGROUND OF THE INVENTION

Pulse oximetry is a widely accepted noninvasive procedure for measuring the oxygen saturation level of arterial blood, an indicator of a person's oxygen supply. A typical pulse oximetry system utilizes an optical sensor clipped onto a fingertip to measure the relative volume of oxygenated hemoglobin in pulsatile arterial blood flowing within the fingertip. Oxygen saturation (SpO_2), pulse rate and a plethysmograph waveform, which is a visualization of pulsatile blood flow over time, are displayed on a monitor accordingly.

Conventional pulse oximetry assumes that arterial blood is the only pulsatile blood flow in the measurement site. During patient motion, venous blood also moves, which causes errors in conventional pulse oximetry. Advanced pulse oximetry processes the venous blood signal so as to report true arterial oxygen saturation and pulse rate under conditions of patient movement. Advanced pulse oximetry also functions under conditions of low perfusion (small signal amplitude), intense ambient light (artificial or sunlight) and electrosurgical instrument interference, which are scenarios where conventional pulse oximetry tends to fail.

Advanced pulse oximetry is described in at least U.S. Pat. Nos. 6,770,028; 6,658,276; 6,157,850; 6,002,952; 5,769,785 and 5,758,644, which are assigned to Masimo Corporation ("Masimo") of Irvine, Calif. and are incorporated by reference herein. Corresponding low noise optical sensors are disclosed in at least U.S. Pat. Nos. 6,985,764; 6,813,511; 6,792,300; 6,256,523; 6,088,607; 5,782,757 and 5,638,818, which are also assigned to Masimo and are also incorporated by reference herein. Advanced pulse oximetry systems including Masimo SET® low noise optical sensors and read through motion pulse oximetry monitors for measuring SO_2, pulse rate (PR) and perfusion index (PI) are available from Masimo. Optical sensors include any of Masimo LNOP®, LNCS®, Soffouch™ and Blue™ adhesive or reusable sensors. Pulse oximetry monitors include any of Masimo Rad-8®, Rad-5®, Rad®-5v or SatShare® monitors.

Advanced blood parameter measurement systems are described in at least U.S. Pat. No. 7,647,083, filed Mar. 1, 2006, titled Multiple Wavelength Sensor Equalization; U.S. patent application Ser. No. 11/367,036, filed Mar. 1, 2006, titled Configurable Physiological Measurement System; U.S. patent application Ser. No. 11/367,034, filed Mar. 1, 2006, titled Physiological Parameter Confidence Measure and U.S. patent application Ser. No. 11/366,208, filed Mar. 1, 2006, titled Noninvasive Multi-Parameter Patient Monitor, all assigned to Masimo Laboratories, Irvine, Calif. (Masimo Labs) and all incorporated by reference herein. Advanced blood parameter measurement systems include Masimo Rainbow® SET, which provides measurements in addition to SO_2, such as total hemoglobin (SpHb™), oxygen content (SpOC™), methemoglobin (SpMet®), carboxyhemoglobin (SpCO®) and PVI®. Advanced blood parameter sensors include Masimo Rainbow® adhesive, ReSposable™ and reusable sensors. Advanced blood parameter monitors include Masimo Radical-7™, Rad-87™ and Rad-57™ monitors, all available from Masimo. Such advanced pulse oximeters, low noise sensors and advanced blood parameter systems have gained rapid acceptance in a wide variety of medical applications, including surgical wards, intensive care and neonatal units, general wards, home care, physical training, and virtually all types of monitoring scenarios.

SUMMARY OF THE INVENTION

Advantageously, a plethysmographic respiration processor provides respiration rate readings based upon optical properties of pulsatile blood flow. The respiration rate so derived may be used alone or combined with respiration rate derived by various other means including, but not limited to, microphones or other acoustic sensors located to respond to various body sounds; humidity sensors located to respond to inhalation/exhalation moisture; thermistors and photodiodes located to respond to inhalation/exhalation air temperature; capacitance sensors located to respond to inhalation/exhalation air pressure; and venturi effect sensors located to respond to inhalation/exhalation air flow. In a particularly advantageous embodiment, a plethysmographic respiration detector is used in conjunction with an acoustic monitor or combined blood parameter and acoustic monitor, such as a Masimo Rainbow® SET platform and an acoustic respiration rate (RRa™) sensor available from Masimo, so as to improve the accuracy of, robustness of, or otherwise supplement acoustic-derived respiration rate measurements or other acoustic-derived respiration parameters.

One aspect of a plethysmographic respiration processor is responsive to respiration affecting blood volume and a corresponding detected intensity waveform measured with an optical sensor at a blood perfused peripheral tissue site so as to provide a measurement of respiration rate. The plethysmographic respiration detector comprises a preprocessor, processors and decision logic. The preprocessor identifies a windowed pleth corresponding to a physiologically acceptable series of plethysmograph waveform pulses. The processors derive various spectrums of the windowed pleth. Each of the processors is configured so that its corresponding spectrum is particularly responsive to a specific respiratory effect on the windowed pleth. The decision logic determines a respiration rate based upon matching features of at least two of the spectrums.

In various embodiments, the processors comprise a baseline processor that inputs the windowed pleth and outputs a "baseline" spectrum. The baseline processor has a first signal conditioner and a first frequency transform. The first signal conditioner generates a first conditioned pleth from the windowed pleth. The first frequency transform inputs the first conditioned pleth and generates the baseline spectrum.

The processors further comprise an amplitude modulation (AM) processor that inputs the windowed pleth and outputs an "AM" spectrum. The AM processor has a second signal conditioner that generates a second conditioned pleth from the windowed pleth. A demodulator AM demodulates the second conditioned pleth to generate a demodulated pleth. A

second frequency transform inputs the demodulated pleth and generates the AM spectrum.

The processors further comprise a shape modulation (SM) processor that inputs the windowed pleth and outputs a "SM" spectrum. The SM processor has a third signal conditioner that generates a third conditioned pleth from the windowed pleth. A feature extractor generates a modulated metric from the third conditioned pleth. A third frequency transform generates the SM spectrum from the modulated metric.

The decision logic has a peak detector, a comparator and a respiration rate output. The peak detector operates on at least two of the baseline spectrum, the AM spectrum and the SM spectrum so as to determine local maximums. The comparator determines if there are any local maximums from the at least two of the spectrums that occur at matching frequencies within a predetermined tolerance. A respiration rate output is generated if the comparator finds at least a two-way match. A smoother operates on multiple respiration rate outputs derived over a sliding series of the windowed pleths so as to derive a smoothed respiration rate output. A tested condition rejects the respiration rate output if it differs from the smoothed respiration rate output by more than a predetermined amount.

Another aspect of a respiration rate processor is inputting a plethysmograph waveform, determining a baseline spectrum responsive to a respiratory-induced baseline shift of the plethysmograph waveform, determining an amplitude modulation (AM) spectrum responsive to a respiratory-induced amplitude modulation of the plethysmograph waveform, determining a shape modulation (SM) spectrum responsive to a respiratory-induced shape modulation of the plethysmograph waveform, and matching at least two of the baseline, AM and SM spectrums so as to derive a respiration rate. In an embodiment, determining a baseline spectrum comprises frequency transforming the plethysmograph waveform. In an embodiment, determining an AM spectrum comprises demodulating the plethysmograph waveform so as to generate a demodulated pleth; and frequency transforming the demodulated pleth. In an embodiment, determining a SM spectrum comprises feature extracting the plethysmograph waveform so as to generate a modulated metric and frequency transforming the modulated metric.

In various other embodiments, matching comprises detecting peaks in at least two of the spectrums, comparing the detected peaks so as to find one peak from each of the at least two spectrums occurring at a particular frequency and outputting the particular frequency as the respiration rate. Windowed pleths are defined by a sliding window of acceptable portions of the plethysmograph waveform. The respiration rate output is smoothed based upon a median respiration rate calculated over multiple ones of the windowed pleths. The particular frequency is rejected if it is not within a predetermined difference of the smoothed respiration rate.

A further aspect of a respiration rate processor is a baseline processor, an AM processor, a SM processor and decision logic. The baseline processor identifies a respiration-induced baseline shift in a plethysmograph waveform. The AM processor identifies a respiration-induced amplitude modulation of the plethysmograph waveform. The SM processor identifies a respiration-induced shape modulation of the plethysmograph waveform. The decision logic compares the respiration-induced baseline shift, amplitude modulation and shape modulation so as to derive a respiration rate.

In various embodiments, the baseline processor generates a baseline spectrum from a first frequency transform of the plethysmograph waveform. The AM processor generates an AM spectrum from a second frequency transform of demodulated plethysmograph waveform. The SM processor generates an SM spectrum from a third frequency transform of a modulated metric extracted from the plethysmograph waveform. Decision logic has a peak detector and a comparator. The peak detector determines local maximums in each of the baseline spectrum, AM spectrum and SM spectrum. In an embodiment, the comparator determines a three-way match in the frequency of the local maximums in the spectrums. In an embodiment, the comparator determines a two-way match in the frequency of the local maximums in the spectrums, and a condition for accepting the two-way match compares a respiration rate determined by the two-way match to a smoothed respiration rate.

A further aspect of a plethysmographic respiration processor is responsive to respiratory modulation of a blood volume waveform or corresponding detected intensity waveform measured with an optical sensor at a blood perfused peripheral tissue site so as to provide a measurement of a respiration parameter. A demodulator processes a sensor signal so as to generate a plethysmograph waveform. A pulse processor identifies candidate pulses from the plethysmograph waveform. A pulse modeler identifies physiologically acceptable ones of the candidate pulses. The plethysmographic respiration processor has a feature extractor, a normalizer and a feature analyzer. The feature extractor processes the acceptable pulses so as to calculate pulse features. The normalizer compares the pulse features so as to calculate a pulse parameter. The feature analyzer calculates a respiration parameter from the pulse parameter.

In various embodiments, the pulse features comprise a difference (E) between an acceptable pulse and a triangular pulse estimate; the pulse features comprise an area (A) under a triangular pulse; or the pulse features are calculated with respect to a diastolic (d) portion of an acceptable pulse and a corresponding diastolic portion of a triangular pulse. In various embodiments, the normalizer compares a diastolic difference (Ed) with a diastolic area (Ad) or the normalizer calculates Ed/Ad. In an embodiment, the feature analyzer determines the frequency spectrum of Ed/Ad so as to determine a respiration rate.

Yet another aspect of a plethysmographic respiration processor detects a tissue site response to optical radiation having a plurality of wavelengths, demodulates the response according to wavelength so as to generate a corresponding plurality of plethysmograph waveforms, identifies acceptable pulses from at least one of the waveforms and calculates a respiration parameter from the acceptable pulses. To calculate a respiration parameter, in various embodiments the processor estimates an acceptable pulse with a triangular pulse and determines a systolic portion and a diastolic portion of the acceptable pulse and the triangular pulse; compares the triangular to the acceptable pulse so as to define pulse features; normalizes the pulse features according to the systolic and diastolic portions so as to generate a pulse parameter; or analyzes the pulse parameter to derive a respiration parameter. The comparing may comprise differencing the acceptable pulse and the triangular pulse over the diastolic portion. The analyzing may comprise transforming the pulse parameter to a frequency parameter and outputting a respiration rate according to a maximum of the frequency parameter.

Additional aspects of plethysmographic respiration processor has a pulse input having physiologically acceptable

pleth pulses derived from a plethysmograph waveform. A feature extractor extracts pulse features from the pulse input. The pulse features are modulated by respiration. A normalizer calculates a pulse parameter from the relative magnitude of a first one of the pulse features compared with a second one of the pulse features. A feature analyzer calculates a respiration parameter from the pulse parameter.

In various embodiments, the feature extractor may calculate a difference between a triangular pulse estimate and a corresponding pleth pulse. The feature may also calculate an area under a portion of the triangular pulses. The processor may differentiate between a systolic pulse feature and a diastolic pulse feature. The feature extractor may calculate an apex angle of the slope portion of a triangular pulse estimate. The feature analyzer may perform a frequency transform to extract a respiration rate from the pulse parameter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a plethysmographic respiration processor embodiment;

FIGS. **2**A-B are a block diagram of a pre-processor embodiment and a time illustration of a sliding window, respectively;

FIGS. **3**A-C are a block diagram of a baseline processor, an intensity versus time graph of a baseline modulated pleth, and a baseline frequency spectrum, respectively;

FIGS. **4**A-D are a block diagram of an AM processor, an intensity versus time graph of an AM pleth, and AM pleth frequency spectrum and a demodulated pleth frequency spectrum, respectively;

FIGS. **5**A-D are a block diagram of an SM processor, an intensity versus time graph of an SM pleth, and graph of a shape metric versus time; and a shape metric frequency spectrum, respectively;

FIGS. **6**A-B are intensity versus time graphs of a shape modulated pulse illustrating area-based shape metrics;

FIGS. **7**A-B are intensity versus time graphs of a shape modulated pulse illustrating arc-length shape metrics;

FIG. **8**A-D are a block diagram of an FM processor, an intensity versus time graph of an FM pleth, and graph of a dicrotic-notch based FM metric versus time; and a FM metric frequency spectrum, respectively;

FIG. **9** is a block diagram of a pre-processor embodiment;

FIG. **10** is a block diagram of a plethysmographic respiration processor embodiment;

FIGS. **11**A-D are a spectrums of a combined baseline shifted and AM modulated pleth; a spectrum of a demodulated baseline shifted and AM modulated pleth; a SM spectrum; and a non-idealized spectrum, respectively;

FIG. **12** is a decision logic flowchart for advantageously deriving a robust value for respiration rate based upon a baseline, an AM and a SM processor operating on an acceptable window of pleths; and

FIG. **13** is a decision logic flowchart for advantageously deriving a robust value for respiration rate based upon a baseline, an AM and a high pass filtered (HPF) SM processor operating on an acceptable window of pleths.

FIG. **14** is a perspective view of a non-invasive physiological parameter measurement system having a monitor and a corresponding optical sensor and incorporating a plethysmographic respiration processor;

FIGS. **15**A-B are graphs of light absorption profiles for pulsatile blood perfused tissue and surrounding tissue and an optical sensor detected light intensity, respectively;

FIG. **16** is block diagram of a non-invasive physiological parameter measurement system having a monitor and a corresponding optical sensor and incorporating a plethysmographic respiration processor; and

FIG. **17** is a block diagram of a modulated plethysmograph demodulator.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** illustrates a plethysmographic respiration processor **100** embodiment having a plethysmograph waveform (pleth) input **101** and a respiration rate (RR) output **104**. The pleth respiration processor **100** includes a preprocessor **200**, one or more pleth processors **120** and a post processor **130**. The pleth **101** is derived from an optical sensor attached to a tissue site, which is in communications with a pulse oximeter or blood parameter monitor, as described with respect to FIGS. **14-17**, below. The pre-processor **200** derives acceptable pleths **112**, as described in detail with respect to FIGS. **2**A-B, below. The pleth processor(s) **120** each operate on acceptable pleths **112** so as to generate respiration-rated parameters **102** responsive to a person's respiration. The pleth processors **120** may operate in the time domain, the frequency domain or a mix of time or frequency domains. Pleth processors **120** are described in detail with respect to FIGS. **3-8**, below. The post-processor **130** resolves or otherwise verifies the respiration-related parameters **102** so as to derive a respiration rate and, perhaps, averages, smoothes or otherwise filters that respiration rate so as to generate the respiration rate (RR) **104** output. Advantageously, this optical sensor derived RR may be used to derive a less intrusive measure of respiration rate or used in combination with acoustic, mechanical, electrical, temperature or other sensors and monitors so as to determine a more accurate or robust measure of respiration rate. Although described herein as deriving a respiration rate, a plethysmographic respiration processor **100** output may be similarly expressed as a respiration or a breathing frequency or interval, among others.

FIGS. **2**A-B illustrate a pre-processor **200** having a pleth **101** input and generating a conditioned pleth **112**, as described below. The pre-processor **200** has a candidate pulse processor **220**, a pulse modeler **230**, a sliding window **240**, a pleth windower **250** and a signal conditioner **260**. A single pleth channel is selected from a multiple demodulated pleths **1705** (FIG. **17**) as a representative pleth **101** input. In an embodiment, the representative pleth channel corresponds to the IR wavelength channel of a (two wavelength) pulse oximeter.

As shown in FIG. **2**A, the pleth **101** is fed into a candidate pulse processor **220** that removes noise and artifacts and identifies the start and end of pulses that conform to various tests of physiological acceptability. In an embodiment, the candidate pulse processor **220** has curvature, low-pass filter and edge finder components that remove waveform features that do not correspond to the steep inflow phase during ventricular systole or the longer outflow phase during diastole, including the characteristic dichrotic notch and miscellaneous waveform curvature changes. Accordingly, the candidate pulse processor **220** identifies "edges" within an input waveform segment that connect a peak and subsequent valley of a pleth pulse. The candidate pulse processor **220** also has delta T, zero crossing, amplitude threshold and slope checks so as to eliminate certain of the edges that were identified by the curvature, filter and edge finder components that do not meet certain conditions. The delta T

discards all the edges that are either too slow or too quick to be physiological. The zero crossing check eliminates all edges that do not cross the zero line, such as small bumps that are not peaks or valleys. The amplitude threshold check removes larger "bumps" than the zero crossing check, such as dicrotic notches. The slope check is based on the observation that in a physiological pulse, the ventricular contraction, i.e. descending pulse portion, is steeper than any subsequent trend in the ascending pulse portion. The pulse finder transforms the edges remaining after the various edge checks into candidate pulses **222**, which are fed into the pulse modeler **230**.

Also shown in FIG. **2**A, the pulse modeler **230** takes the candidate pulses **222** and identifies which of these are acceptable pulses **232**, which satisfy an internal model for a physiological plethysmographic waveform. Although the candidate pulse processor **220** performs a series of checks on edges, the pulse modeler **230** performs a series of checks on pulse features. The first component of the pulse modeler calculates relevant pulse features. The remainder of the pulse modeler checks these pulse features to identify physiologically acceptable features. The pulse features component extracts three items of information about the input candidate pulses that are needed for downstream processing by the other components of the pulse modeler including pulse starting point, period and signal strength. The downstream components include a max BPM check, a stick model check, an angle check, a ratio check and a signal strength check. The maximum beats-per-minute (max BPM) check discards pulses having a period that is below a minimum number of samples. The stick model check discards pulses where the corresponding waveform does not fit a stick model. The angle check is based on computing the angle of a normalized slope for the ascending portion of a pulse so as to discard pulses that are extremely asymmetric. The ratio check removes pulses in which the ratio between the duration of the ascending pulse portion and the duration of the descending pulse portion is less than a certain threshold. The signal strength check assigns a confidence value to each pulse, based on its signal strength, and low confidence pulses are discarded. A pulse processor **220** and a pulse modeler **230** are described in U.S. Pat. No. 6,463,311 titled Plethysmograph Pulse Recognition Processor, issued Oct. 8, 2002, assigned to Masimo Corporation and incorporated by reference herein.

Further shown in FIGS. **2**A-B, the sliding window **240** defines a series of fixed-time-length (T) samples ("windows") of pleth, where each window **242** is shifted from the previous window by a fixed time interval (At) **244**. In an embodiment, each window is T=2125 samples (34 sec) in length at 16 msec per sample (62.5 Hz sample rate), where successive windows are shifted by Δt=2 sec. Each window is either accepted **242** or rejected **248** as designated by an acceptable window **242** output. The pleth windower **250** utilizes the acceptable windows **242** designation to accept a corresponding section of the "raw" pleth **101** input and generate a windowed (raw) pleth **252** output. That is, the pre-processor **200** advantageously allows downstream processing to operate directly on the demodulated pleth while discarding those raw pleth sections that are deemed unacceptable, based upon various pleth models and checks as described above. In an embodiment, the signal conditioner **260** demeans/detrends and bandpass filters the windowed pleth **252** to generate a conditioned pleth **112** output. In an embodiment, the bandpass filter is an IIR filter having a 12-240 bpm (beats per minute) passband. In another embodiment described below with respect to FIG. **9**, below, a pre-processor **200** generates windowed features from acceptable pulses derived from the pleth **101** input.

FIGS. **3**A-B illustrate a baseline processor **300** that derives a "baseline" spectrum F_b **302** responsive to a respiration-induced baseline shift in a pleth. As shown in FIG. **3**A, the baseline processor **300** has a conditioned pleth **301** input and generates a corresponding baseline spectrum F_b **302**. As shown in FIG. **3**B, the conditioned pleth **301** has a pleth period **381** inversely related to pulse rate (PR). Under certain conditions, an individual's respiration induces a cyclical shift in the pleth baseline **382**. The cyclical shift period **383** is inversely related to respiration rate (RR). As shown in FIG. **3**C, a frequency spectrum **302** of the baseline-shifted pleth **301** includes a relatively large pulse rate (PR) peak **392** and a relatively small respiration rate (RR) peak **391**.

In other embodiments, a baseline processor **300** employs a time domain calculation of the conditioned pleth **301** that determines the period **383** of a cyclical baseline shift and hence respiration rate. Such a time domain calculation may be based upon envelope detection of the conditioned pleths **301**, such as a curve-fit to the peaks (or valleys) of the pleth pulses. Measurements of a cyclical variation in a plethysmograph baseline are described in U.S. patent application Ser. No. 11/221,411 titled Noninvasive Hypovolemia Monitor, filed Sep. 6, 2005 and published as US 2006/0058691 A1, assigned to Masimo and incorporated by reference herein.

FIGS. **4**A-B illustrate an AM processor **400** that derives an "AM" spectrum F_{am} **402** responsive to a respiration-induced amplitude modulation of the pleth. As shown in FIG. **4**A, the AM processor **400** has a conditioned pleth **401** input and generates a corresponding AM spectrum F_{am} **402** that is responsive to a demodulated pleth **422**. In an embodiment, the demodulator **420** squares, low pass filters (LPF) and square-roots the conditioned pleth **401** to generate a demodulated pleth **422**. In an embodiment, the frequency transformation **430** utilizes a Hamming window, a chirp-Z FFT algorithm and a magnitude calculation so as to generate an AM spectrum **402** for the demodulated pleth **422**.

As shown in FIG. **4**B, a pleth **401** has a pleth period **471** inversely related to pulse rate (PR). Under certain conditions, an individual's respiration amplitude modulates (AM) **472** the plethysmograph **401**. In particular, the modulation period **473** is inversely related to respiration rate (RR). As shown in FIG. **4**C, a spectrum **480** of the pleth **401** includes a pulse rate (PR) peak **481** and respiration sidebands **482**, **483** displaced by RR on either side of the PR peak **481**. As shown in FIG. **4**D a spectrum **402** of the demodulated pleth **422** includes a DC peak **491** resulting from the demodulated pulse rate "carrier" translated to DC and a respiration rate (RR) peak **492** resulting from the demodulated sidebands **482**, **483**.

An AM processor **400** is described above as demodulating **420** a conditioned pleth **401**. In other embodiments, a time domain calculation of the conditioned pleth **401** determines the respiration modulation period **473** and hence the respiration rate. That time domain calculation may be based upon envelope detection of the conditioned pleth **401**, such as a curve-fit to the peaks (or valleys) of the plethysmograph or, alternatively, the peak-to-peak variation. Measurements of variation in a plethysmograph envelope are described in U.S. patent application Ser. No. 11/952,940 titled Plethysmograph Variability Processor, filed Dec. 7, 2007 and published as US 2008/0188760 A1, assigned to Masimo and incorporated by reference herein.

FIGS. **5**A-D illustrate a shape modulation (SM) processor **500** that derives an "SM" spectrum F_s **502** responsive to a respiration-induced shape modulation of the pleth. As shown in FIG. **5**A, the SM processor **500** has a conditioned pleth **501** input and generates a corresponding SM spectrum F_s **502**. In an embodiment, the SM processor **500** includes a feature extractor **520**, a high pass filter (HPF) **530** and a frequency transform **540**. In another embodiment, the SM processor includes the feature extractor **520** and a frequency transform **540**, but excludes the high pass filter **530**. The feature extractor **520** generates a shape-based modulated metric **522**, such as E/A described below. In an embodiment, the HPF **530** is a time domain difference filter that calculates Y_{n+1}-Y_n so as to remove an erroneous first (low frequency) peak in the SM spectrum F_s **502**. In an embodiment, the frequency transformation **540** utilizes a Hamming window, a chirp-Z FFT algorithm and a magnitude calculation so as to generate the SM spectrum **502** for each windowed conditioned pleth **501**.

As shown in FIG. **5**B, a pleth **501** has a pleth period **571** inversely related to pulse rate (PR). Under some circumstances, an individual's respiration modulates the shape of each pleth pulse. This modulation may be described in terms of a predefined pleth feature or "shape metric." In an advantageous embodiment, a shape metric is defined by a difference or "error" E **572** between the diastolic portion of a pleth pulse and its corresponding triangular pulse approximation, normalized by the area A **573** under the triangular pulse approximation.

As shown in FIG. **5**C, a respiration-modulated shape metric **522** has a cyclical period **581** inversely related to respiration rate (RR). As shown in FIG. **5**D, a spectrum **502** of the modulated shape metric **522** includes a respiration rate (RR) peak **591**.

A SM processor **500** is described above as based upon a normalized diastolic error metric (E/A). In other embodiments, shape metrics may be based upon other pulse features such as a diastolic area, error or angle normalized by the corresponding systolic area, error or angle (Ad/As, Ed/Es, θd/θs), or shape metrics may be related to the arc length of the diastolic and/or systolic portions of a pleth pulse, to name a few. These and other pulse shapes and features responsive to respiration are also contemplated herein.

FIGS. **6**A-B further illustrates pulse shape features that are derived by a feature extractor **520** (FIG. **5**A) embodiment. Acceptable pleth pulses **610** are generated by the pre-processor **200** (FIG. **2**A), as described above. For convenience of illustration, the inverse of an "intensity" pulse is shown, as described with respect to FIGS. **15**A-B, below. The pleth pulse **610** has a peak Y at a time Wand corresponding valleys at times X and Z. The peak and valleys define a triangular pulse **620** XYZ that approximates the pleth pulse **610**. Further, the time line WY corresponding to the peak Y divides the pleth pulse **610** into a systolic portion **630** and a diastolic portion **640**.

As shown in FIG. **6**A, a systolic error Es **631** is defined as the total area between the pleth pulse **610** and the approximate triangular pulse **620** within the systolic portion **630**. A diastolic error Ed **641** is defined as the total area between the pleth pulse **610** and the triangular pulse **620** within the diastolic portion **640**.

As shown in FIG. **6**B, a systolic area As **632** is defined as the total area under the triangular pulse **620** within the systolic portion **630**. A diastolic area Ad **642** is defined as the total area under the triangular pulse **620** within the diastolic portion **640**. A systolic angle θs **633** is defined as the angle XYW defined by the triangular pulse within the systolic portion **630**. A diastolic angle θd **643** is defined as the angle ZYW defined by the triangular pulse within the diastolic portion **640**.

Based upon the above-described pulse feature definitions, normalized pulse features may be defined. These may include normalized diastolic pulse features, such as Ed/Ad, corresponding to the diastolic triangular pulse error normalized by the diastolic triangular pulse area. Other normalized diastolic pulse features may include a diastolic area, error or angle normalized by the corresponding systolic area, error or angle (Ad/As, Ed/Es, θd/θs).

FIGS. **7**A-B illustrate additional pulse shape features. As shown in FIG. **7**A, pulse features may be based upon the length of a curve (trace, arc, path or line) portion of a pleth pulse **710**. In particular, a diastolic curve length Ld **745** between the pulse peak Y and valley Z is defined in polar coordinates as:

$$Ld = \int_Y^Z \sqrt{r^2 + \left(\frac{dr}{d\theta}\right)^2}\, d\theta \qquad \text{(EQ. 1)}$$

where r is the distance from W (time corresponding to the peak Y) to any point V along the curve **710** and θ is the angle between r and the time axis WZ. Ld **745** may be similarly defined in Cartesian coordinates. A systolic curve length Ls **735** may be defined in similar fashion. A normalized length pulse feature Ld/Ls may be defined accordingly. In other embodiments, pulse features Ld **745** or Ls **735** may be normalized by the diastolic **640** or systolic **630** areas or angles defined with respect to FIG. **6**B, above. In various embodiments, pulse features Ld **745** or Ls **735** also may be normalized by pulse height WY, by diastolic WZ or systolic XW pulse widths, by total pulse width XZ or by mathematical combinations of these measures of pulse height and pulse width to name a few.

As shown in FIG. **7**B, pulse shape features may be based upon the curvature of a portion of a pleth pulse **710**. In particular, a curvature Λ is defined in pedal coordinates as:

$$\kappa = \frac{1}{r}\frac{dp}{dr} \qquad \text{(EQ. 2)}$$

where the pedal coordinates of a point V with respect to the pulse **710** and the pedal point W are the radial distance r from W to V and the perpendicular distance p from W to the line t tangent to the pulse **710** at V, as shown. K may be similarly defined in Cartesian or polar coordinates. Total curvature K of a curve segment between points a and b is then

$$K = \int_a^b \kappa(s)ds \qquad \text{(EQ. 3)}$$

A diastolic curvature Kd **746** or systolic curvature Ks **736** pulse shape feature may be defined accordingly. In other embodiments, a curvature pulse shape feature may be defined according to the absolute value of the maximum and/or minimum curvature of the pulse **710** or pulse segment **730**, **740**, or the curvature of a particular feature, such as a dicrotic notch. In other embodiments, pulse shape features Kd **746** or Ks **736** may be normalized by the diastolic **640** or systolic **630** areas or angles defined above with respect to

FIGS. **6**A-B. In various embodiments, pulse features Kd **746** or Ks **736** also may be normalized by pulse height WY, by diastolic WZ or systolic XW pulse widths, by total pulse width XZ or by mathematical combinations of these measures of pulse height and pulse width to name a few. In other embodiments, various normalized systolic and/or diastolic pulse features may be similarly defined.

FIG. **8**A-D illustrate an FM processor **800** that derives an "FM" spectrum F_{fm} **802** responsive to a respiration-induced frequency modulation of the pleth. As shown in FIG. **8**A, the FM processor **800** has a conditioned pleth **112** input and generates a corresponding FM spectrum F_{fm} **802** that is responsive to a demodulated pleth **822**. In an embodiment, the demodulator **820** utilizes a metric Δ responsive to the time difference between identifiable epochs of each pleth pulse. In an embodiment, the epochs are based upon a dicrotic notch. In an embodiment, the metric Δ is the time difference between two identifiable portions of a dicrotic notch such as the notch local maximum, local minimum, or mid-point between local maximum and local minimum, to name a few.

As shown in FIG. **8**B, a pleth **801** has a pleth period **871** inversely related to pulse rate (PR). Under certain conditions, an individual's respiration frequency modulates (FM) the plethysmograph **801**. In particular, the modulation period **881** (FIG. **8**C) is inversely related to respiration rate (RR). FIG. **8**C illustrates a respiration-modulated FM metric **822** over time. In particular, an FM metric **822**, such as the metric Δ described above, has a cyclical period **881** inversely related to respiration rate (RR). As shown in FIG. **8**D, a spectrum **802** of the FM metric **822** includes a respiration rate (RR) peak **891**.

FIG. **9** illustrates another pre-processor **900** embodiment having a pleth **101** input and generating a windowed features **962** output. The pre-processor **900** has a candidate pulse processor **220** and pulse modeler **230** that operate on the pleth **101** input so as to generate an acceptable pulses **232** output, as described with respect to FIG. **2**A, above. Further, the pre-processor **900** has a time base standard **940**, a feature extractor/normalizer **950**, and a windowing/outlier rejecter **960**. The time base standard **940** inputs acceptable pulses **941** and outputs resized pulses **942**. In particular, the time base standard **940** mathematically re-samples the input pulses **941** so that each pulse has the same number of samples. For example, if a standard pulse has 50 samples and an input pulse **941** has 60 samples, then the input pulse **941** sample interval is made larger by 60/50 or 1.2 times so that the resized input pulse width is 50 samples. Similarly, if an input pulse **941** has 40 samples, then the input pulse **941** sample interval is made smaller by 40/50 or 0.8 times so that the resized input pulse width is 50 samples. A resized input pulse is derived by interpolating the original pulse at re-sampled points. For example, a linear interpolation embodiment is used according to the following

$$y = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(x - x_1) + y_1 \qquad \text{(EQ. 4)}$$

where $X_2 - X_1$ is the original sample interval; Y_1 and Y_2 are input pulse **401** values at X_1 and X_2, respectively; x is a resized sample point between X_1 and X_2 and y is the resized pulse value at x. In other embodiments, the interpolation is a cubic spline or a polynomial interpolation to name a few.

Also shown in FIG. **9**, the feature extractor/normalizer **950** inputs the resized pulses **942** described above and outputs normalized pulse features **952**. Pulse features may include one or more of the differences or "errors" E between an acceptable pulse and its corresponding triangular pulse; areas A under the triangular pulse; and apex angles θ of a triangular pulse, to name a few, as described in detail with respect to FIGS. **6-7**, above. Pulse features may also distinguish between a steeper-slope portion corresponding to systole S and a shallower-slope portion corresponding to diastole D. Pulse features are normalized by comparing one or more extracted features with one or more other extracted features. In an embodiment, normalized pulse features **952** advantageously include Ed/Ad corresponding to the diastolic triangular pulse error normalized by the diastolic triangular pulse area. Other normalized pulse features **952** may include a diastolic area, error or angle normalized by the corresponding systolic area, error or angle (Ad/As, Ed/Es, θd/θs). These and additional normalized pulse features relating to an acceptable pulse and/or its corresponding triangular pulse are also contemplated herein and described with respect to FIGS. **6-7**, above.

Further shown in FIG. **9**, the windowing/outlier rejecter **960** inputs the normalized features **952** and outputs windowed features **962**. The windowed features **962**, in turn, may be frequency transformed or analyzed in the time domain to determine a respiration modulation of the features, as described above. In particular, windowing **960** defines a sample size (window size) of the normalized features **952**. The outlier rejector **960** calculates a mean or median of the normalized features **952** falling within the window, defines an acceptable range around the mean or median and rejects normalized features falling outside of that acceptable range.

Window size may be a function of a respiration rate (RR) **964**, a heart rate (HR) **966** or both. In particular, HR **966** corresponds to the input pulse **101** frequency and hence determines the time between samples of the normalized features **952**. RR **964** corresponds to the number of feature cycles within a window and hence sets a lower limit on the window size in order to resolve the frequency of those feature cycles.

Pulse rates may typically vary from a resting rate of 40-60 BPM for athletes to 60-90 BPM for non-athletes. Maximum heart rates are typically defined as 220—age. Hence, pulse rates might typically range from 50 to 200 BPM, which is a 4:1 variation in time between samples (0.3 sec to 1.2 sec). Respiration rates may typically vary between 12-20 breaths per minute for resting adults to 35-45 breaths per minute for exercising adults. Hence RR may typically range from 10-50 breaths per minute, which is a 5:1 variation in the number of respiration cycles per window. Accordingly, the number of pulse feature samples per respiration cycle may have a 20:1 variation.

Windowing **960** may be fixed or adjustable. Further, successive windows may be overlapping, i.e. a sliding window may be used, or may be adjacent and non-overlapping. A typical window size may range, say, between 15-120 sec. or more. Accordingly, a window size may encompass, say, 20 respiration cycles at 10 breaths per minute over a 120 sec. window to 12 respiration cycles at 50 breaths per minute over a 15 sec. window. In an embodiment, the window size is adaptively adjusted based upon detected RR and PR.

FIG. **10** illustrates a plethysmographic respiration processor **1000** embodiment having a conditioned plethysmograph waveform (pleth) **112** input and a smoothed respiration rate (RRs) **1005** output. The respiration processor **1000** includes parallel processors **1020**, decision logic **1100-1300** and a smoother **1030**. The conditioned pleth **112** contains pleth

sections corresponding to sliding acceptable windows designated by the pre-processor **200** (FIG. **2**A), as described above with respect to FIGS. **2**A-B. The parallel processors **1020** each operate on conditioned pleth **112** so as to generate frequency spectrums **1022** responsive to respiration rate. The parallel processors **1020** include a baseline processor **300**, an amplitude modulation (AM) processor **400**, a high pass filtered (HPF) shape modulation (SM) processor **500** and a SM processor **501**. In particular, the baseline processor **300** derives a "baseline" spectrum F_b **302** responsive to a respiration-induced baseline shift in a pleth. The baseline processor **300** is described in detail with respect to FIGS. **3**A-C, above. The AM processor **400** derives an "AM" spectrum F_{am} **402** responsive to a respiration-induced amplitude modulation of the pleth. The AM processor **400** is described in detail with respect to FIGS. **4**A-D, above. The SM processors **500**, **501** derive "SM" spectrums F_s **502**, F_s' **504** each responsive to a respiration-induced shape modulation of the pleth. The SM processors **500**, **501** are described in detail with respect to FIGS. **5-7**, above.

As described above, the processors **1020** each generate one spectrum **1022** for each sliding window of the conditioned pleth **112**. Accordingly, the decision logic **1100-1300** attempts to generate a respiration rate (RR) value for each conditioned pleth **112** window. The decision logic **1100-1300** compares two or more of the spectrums F_b, F_{am}, F_s and F_s' **422** so as to calculate a respiration rate (RR) **1004**. If the decision logic **1100-1300** cannot determine a RR **1004** value from the spectrums **1022**, the corresponding conditioned pleth window **112**, is rejected. A smoother **1030** generates a smoothed respiration rate **1005** calculated over multiple respiration rate **1004** values. In an embodiment, the smoother **1030** determines the median value of RR **1004** corresponding to multiple ones of the conditioned pleth windows **112**. In an embodiment, the median value is calculated over five conditioned pleth windows **112**. The decision logic **1100-1300** is described in detail with respect to FIGS. **11-13**, below.

FIGS. **11**A-C illustrate the output of the baseline processor **300** (FIG. **10**), AM processor **400** (FIG. **10**) and SM processor **500** (FIG. **10**), respectively, assuming that a conditioned pleth **112** (FIG. **10**) exhibits each of a baseline shift, an amplitude modulation and a shape modulation due to respiration. As shown in FIG. **11**A, in view of both a respiration-induced baseline shift and AM modulation, the windowed pleth spectrum **1110** is a combination of a baseline shift spectrum **302** (FIG. **3**C) and an AM spectrum **402** (FIG. **4**D). This combination is also the baseline spectrum F_b **302** (FIG. **3**A), i.e. the frequency transform of the conditioned pleth **112**. Hence, in this example, the baseline spectrum **1110** has two possible local maximums or "peaks" **1115**, **1116**. One peak is due to respiration shifting the pleth baseline and one peak is due to respiration amplitude modulating the pleth. However, these peaks cannot be distinguished. In particular, if RR<0.5 PR, then peak **1115** is at a frequency corresponding to RR and peak **1116** is at a frequency corresponding to PR−RR. Likewise, if RR is >0.5 PR, then peak **1115** is at a frequency corresponding to PR−RR and peak **1116** is at a frequency corresponding to RR. That is, "twin" peaks **1115**, **1116** occur symmetrically on either side of frequency ½ PR, one at frequency RR and one at frequency PR-RR, but the peak corresponding to the respiration rate RR cannot be resolved by the baseline processor **302** (FIG. **10**) alone.

As shown in FIG. **11**B, in view of both a respiration-induced baseline shift and AM modulation, the AM spectrum F_{am} **402** (FIG. **10**) is a combination of the spectrums of FIG. **3**C and FIG. **4**C after demodulation. Hence, in this example, the AM processor output **402** (FIG. **10**) has two possible local maximums or peaks **1125**, **1126**. One peak is due to demodulating the pleth corresponding to the spectrum of FIG. **4**C, resulting in the spectrum of FIG. **4**D. The other peak is due to demodulating the pleth corresponding to the spectrum of FIG. **3**C, which translates the pleth fundamental **392** (FIG. **3**C) at PR to DC and the respiration-related peak **391** (FIG. **3**C) to PR-RR. As with the peaks described with respect to FIG. **11**A, these "twin" peaks **1125**, **1126** occur symmetrically on either side of ½ PR, but the peak corresponding to the respiration rate RR cannot be resolved by the AM processor **400** (FIG. **10**) alone.

As shown in FIG. **11**C, the SM spectrum F_s **502** is unaffected by either a baseline shift or by amplitude modulation. In particular, a respiration-induced baseline shift, which shifts the entire pleth waveform up or down, has negligible effect on the error E **572** (FIG. **5**B) or the triangular area A **573** (FIG. **5**B). Further, although respiration-induced AM increases or decreases the pleth amplitude, this is accounted for by normalizing the error E by the triangular area A. As such, in view of both a respiration-induced baseline shift and AM, the SM spectrum F_s **502** is responsive only to shape modulation, as shown in FIG. **5**D, i.e. a single local maximum or peak **1135** occurs at the respiration rate.

As shown in FIGS. **11**A-C, ideally respiration rate may be determined by first verifying the existence of twin peaks **1115**, **1116** symmetric about 0.5 PR in the baseline spectrum **1110** and twin peaks about 0.5 PR in the AM spectrum **1120**. Second, one twin from each spectrum **1110**, **1120** is matched with the single peak in the SM spectrum **1130**. For example, a match between peaks **1115** (FIG. **11**A), **1125** (FIG. **11**B) and **1135** (FIG. **11**C) would provide a robust indication of RR. However, pleths from various sensors, monitors and patients may yield spectrums with erroneous peaks due to physiological conditions or artifact. Accordingly, various peaks and matching conditions are utilized by the decision logic to determine RR, as described with respect to FIGS. **12-13**, below.

As shown in FIG. **11**D, a peak identifying nomenclature **1140** is used in describing decision logic with respect to the baseline spectrum F_b **302** (FIG. **10**) and the AM spectrum F_{am} **402** (FIG. **10**). The largest peak in a spectrum is designated ① and its twin designated ④. If the largest peak is the first peak, which is sometimes erroneous, then the second largest peak is designated ② and its twin designated ⑤. If the largest peak is the last peak, which is also sometimes erroneous, the second largest peak is designated ③ and its twin designated ⑥.

FIG. **12** illustrates the decision logic **1200** for advantageously deriving a robust value for respiration rate based upon each of the baseline **300**, AM **400** and SM **500** processors (FIG. **10**) operating on a conditioned pleth **112** (FIG. **10**). The spectrums F_b, F_{am} and F_s from these processors are input **1210** into the decision logic **1200**. A peak detector **1220** locates the largest peak ① and its twin ④ from each of F_b **1110** (FIG. **11**A) and F_{am} **1120** (FIG. **11**B) and the largest peak ① from F_s **1130** (FIG. **11**C). The comparator **1230** looks for a three-way match from, say, the largest peak from each of the spectrums. This comparison is denoted 1-1-1, designating the largest peaks from the spectrums F_b-F_{am}-F_s, respectively. If the frequencies of all of these peaks match **1240**, within a predetermined error, then that frequency is output as the respiration rate **1250** for that conditioned pleth window **112** (FIG. **10**). If there is no match **1240**, other combinations **1260**, **1266** of peaks of a particular

series are compared **1230**, such as the largest peak from F_b, the twin to the largest peak from F_{am} and the largest peak from F_s, denoted 1-4-1. Hence, all of the following combinations are denoted the first series of combinations to try, i.e. series I: 1-1-1; 1-4-1; 4-1-1; 4-4-1.

As shown in FIG. **12**, if there are no matches from series I, other series **1270**, **1275** having different types of combinations are tried, as explained below. If a particular twin cannot be located, the corresponding series is rejected **1275**. If no 3-way matching peaks are found after trying all combinations in each of series I, II, III, IV **1270**, then that particular window is rejected **1280** and no respiration rate value is determined that corresponds to that window.

Series II represents a second set of peak comparisons. In some cases, the largest peak ① from F_b or F_{am} or both may be the first peak, which is often erroneous. As such, comparisons may be made using the second largest peaks ② from F_b and F_{am} and the corresponding twins ⑤. The twins in this series are verified to exist, but not used. Accordingly, in an embodiment, the largest peaks ① and the second largest peaks ② are compared in the following combinations: 2-1-1; 1-2-1; 2-2-1.

Series III represents a third set of peak comparisons. In some cases, the largest peak from F_b or F_{am} or both may be the last peak, which is also often erroneous. As such, comparisons may be made using the second largest peaks ③ from F_b and F_{am} and the corresponding twins ⑥. Accordingly, in an embodiment, these peaks are compared in the following combinations: 3-3-1; 6-3-1; 3-6-1; 6-6-1.

Series IV represents yet another set of peak comparisons. In some cases, the largest peak from F_s is erroneous. Hence, comparisons may be made using the largest peak from F_s', designated ③, and the largest peak and corresponding twin from F_b and F_{am}, designated ① and ④, as noted above. Accordingly, in an embodiment, these peaks are compared with each other in the following combinations: 4-4-3; 4-1-3; 1-4-3; 1-1-3. In other embodiments, other combinations are possible, for example, the twins to the second largest peaks from F_b and F_{am}, which are designated ⑤, could be used in various combinations with other designated peaks described above. If all combinations fail to yield a three-way match **1240**, then that particular window is rejected **1280**.

FIG. **13** illustrates decision logic **1300** for advantageously deriving a robust value for respiration rate based upon a two-way match of the spectrums F_b, F_{am} and F_s (or F_s') from each of the baseline **300**, AM **400** and shape **500**, **501** processors (FIG. **10**) plus an additional condition **1390**. In an embodiment, decision logic **1300** is used in the event a respiration rate RR **1004** (FIG. **10**) cannot be derived from a three-way match of the spectrums F_b, F_{am} and F_s (or F_s'), as described with respect to FIG. **12**, above.

As shown in FIG. **13**, in a series V, the largest peaks from F_b and F_s, denoted 1_1 (without utilizing F_{am}) are compared for a two-way match **1330**. If there is a match, an additional condition **1370** must be met. In an embodiment, the condition **1390** is that the matching frequencies of F_b and F_s must be within a predetermined difference of the smoothed respiration rate (RRs) **1005** (FIG. **10**). In an embodiment, the predetermined difference is 1 bpm. If so, the matching frequencies are output as the respiration rate RR **1380**. If not, the largest peaks from F_{am} and F_s, denoted _11 (without utilizing F_b) are also compared for a match **1330**. If there is a match from this comparison and the additional condition **1370** is met, then the matching frequencies are output as the respiration rate RR **1380**. If these combinations are compared without a match **1350**, then a series VI is utilized.

Also shown in FIG. **13**, in a series VI, the various peaks from F_b and F_{am}, each denote 1-6, are compared for a two-way match **1330**. If there is a match, the additional condition **1370** must be met. If all combinations, e.g. 11, 12, 13 . . . 21, 22, 23 . . . 36, 46, 56 are tried without a match or there is a match but the additional condition is not met, the window is rejected **1360**. In other embodiments, other peaks are compared **1330** and other conditions **1390** must be met.

FIG. **14** illustrates a physiological monitoring system **1400** that incorporates a plethysmographic respiration processor **100** (FIG. **1**), as described above. The monitoring system **1400** has a monitor **1410**, an optical sensor **1420** and an interconnect cable **1430** connecting the monitor **1410** and sensor **1420**. The monitoring system **1400** generates physiological parameters that indicate one or more aspects of a person's physical condition, including, advantageously, a plethysmograph-derived respiration rate. The sensor **1420** attaches to a tissue site **10**, such as a fingertip, and is capable of irradiating the tissue site **10** with differing wavelengths of light and detecting the light after attenuation by pulsatile blood flow within the tissue site **10**. The monitor **1410** communicates with the sensor **1420** via the interconnect cable **1430** to receive one or more detected intensity signals and to derive from those intensity signals one or more physiological parameters. The monitor also has a display **1413** for presenting parameter values, including respiration rate (RR). Controls **1415** set alarm limits, processing modes, display formats and more. An audio transducer **1416** provides alarm sounds, pulse beeps and button press feedback to name a few. Indicators **1418** show monitor status. The display **1413** may include readouts, colored lights or graphics generated by LEOs, LCOs or CRTs to name a few and is capable of displaying indicia representative of calculated physiological parameters, including respiration rate, and waveforms, including plethysmographs. The display **1413** is also capable of showing historical or trending data related to one or more of the measured parameters or combinations of the measured parameters. User I/O may include, for example, push buttons **1415** and indicators **1418**. The push buttons may be soft keys with display-indicated functions or dedicated function keys **1415**. Other user I/O (not shown) may include keypads, touch screens, pointing devices, voice recognition devices and the like.

FIG. **15**A illustrates a light absorption waveform **1501** at an illuminated peripheral tissue site corresponding to a pulsatile blood volume at that site. The peripheral tissue site is illuminated by, and the corresponding absorption is (indirectly) measured by, an optical sensor **1420** (FIG. **14**), as described above. A y-axis **1530** represents the total amount of light absorbed by the tissue site, with time shown along an x-axis **1540**. The total absorption is represented by layers, including the static absorption layers due to tissue **1532**, venous blood **1534** and a baseline of arterial blood **1536**. Also shown is a variable absorption layer **1538** due to the pulse-added volume of arterial blood that is used to derive a plethysmograph, as described above and further with respect to FIG. **15**B, below. This light absorption waveform **1501** varies as a function of the wavelength of the optical sensor emitted light according to the blood constituency. Indeed, it is this wavelength variation that allows a multi-parameter patient monitor to determine blood hemoglobin components and other blood constituents along with respiration rate characteristics, as described above.

As shown in FIG. **15**A, a pulsatile blood volume **1538** is a function of heart stroke volume, pressure gradient, arterial elasticity and peripheral resistance. The ideal pulsatile blood

volume waveform displays a broad peripheral flow curve, with a short, steep inflow phase **1516** followed by a 3 to 4 times longer outflow phase **1518**. The inflow phase **1516** is the result of tissue distention by the rapid blood volume inflow during ventricular systole. During the outflow phase **1518**, blood flow continues into the vascular bed during diastole. The end diastolic baseline **1514** indicates the minimum basal tissue perfusion. During the outflow phase **1518** is a dicrotic notch **1515**. Classically, the dicrotic notch **1515** is attributed to closure of the aortic valve at the end of ventricular systole. However, it is also a function of reflection from the periphery of an initial, fast propagating pressure pulse that occurs upon the opening of the aortic valve preceding the arterial flow wave. Pulsatile blood volume varies with physiological properties such as heart stroke, vessel size, elasticity and vascularization, to name a few. Accordingly, the blood flow waveform shape can vary significantly from individual to individual and between tissue sites.

FIG. **15**B illustrates a plethysmograph waveform **1502** detected by an optical sensor **1420** (FIG. **14**). In particular, detected intensity is shown along the y-axis **1550** versus time shown along the x-axis **1560**. The plethysmograph waveform **1502** is a time series of plethysmograph ("pleth") pulses and relates to the time-varying pulsatile blood volume **1538** (FIG. **15**A) measured at a particular location on a person, referred to herein as a "tissue site." A tissue site can be a fingertip, ear lobe, toe, nose or forehead to name just as few. A person is used herein as the referenced subject of optical sensor measurements, but other living species also have a measurable pleth and are included within the scope of this disclosure.

As shown in FIG. **15**B, an optical sensor **1420** (FIG. **14**) does not directly detect absorption and, hence, does not directly measure the volume waveform **1538** (FIG. **15**A). However, the plethysmograph waveform **1502** is merely an out-of-phase version of the volume profile **1538**. Stated differently, the plethysmograph waveform **1502** varies inversely with the pulsatile blood volume **1538**. In particular, the peak detected intensity **1554** occurs at minimum volume **1514** and the minimum detected intensity **1552** occurs at maximum volume **1512**. Further, a rapid rise in volume during the inflow phase **1516** is reflected in a rapid decline in intensity **1556**; and the gradual decline in volume during the outflow phase **1518** is reflected in a gradual increase **1558** in detected intensity. The intensity waveform **1502** also displays a dicrotic notch **1555**.

FIG. **16** further illustrates a physiological monitoring system **1600** having an optical sensor **1620** attached to a tissue site **10**, a monitor **1610** and an interconnecting sensor cable **1620**. The sensor **1620** has emitters **1622**, each of which transmit light of a specified wavelength. Drivers **1654**, **1655** convert digital control signals into analog drive signals capable of activating the emitters **1622**. A front-end **1652**, **1653** converts composite analog intensity signal(s) from the detector(s) **1624** into digital data input to a digital signal processor (DSP) **1658**. The DSP **1658** may comprise any of a wide variety of data and/or signal processors capable of executing programs for determining physiological parameters from input data. In an embodiment, the DSP executes firmware **1659** including pre-processors, respiration processors and post processors, such as described with respect to FIGS. **1-13**, above.

Also shown in FIG. **16**, an instrument manager **1682** may comprise one or more microcontrollers controlling system management, such as monitoring the activity of the DSP **1658**. The instrument manager **1682** has an interface port **1683** for monitor communications. In an embodiment, the interface port **1683** has a display driver, an audio driver, user inputs and I/O for driving displays and alarms, responding to buttons and keypads and providing external device input/output communications. In an embodiment, the displays can indicate a variety of physiological parameters **1686** such as respiration rate (RR), pulse rate (PR), plethysmograph (pleth), perfusion index (PI), pleth variability index (PVI), signal quality (IQ) and values for blood constituents including oxygen saturation (SpO_2), carboxyhemoglobin (HbCO), methemoglobin (HbMet), total hemoglobin (Hbt) and oxygen content (OC) as well as instrument and sensor status, such as sensor life, to name but a few.

FIG. **17** illustrates a demodulator **1700** having a modulated/multiplexed detector signal **1703** input and demodulated signal **1705** outputs. That is, the demodulator input **1703** is the result of a detector **1624** (FIG. **16**) response to N emitter wavelengths **1622** (FIG. **16**) that are cyclically turned on and off by emitter drivers **1654** (FIG. **16**) so as to illuminate a tissue site with multiple wavelength optical radiation, as is well known in the pulse oximetry art. The digitized detector signal **1703** corresponds to the A/D converter **1657** (FIG. **16**) input to the DSP **1658** (FIG. **16**). The DSP has demodulator **1700** (preprocessor) firmware **1659** which generates N channels of demodulated signals $r_1(t)$, $r_2(t)$, . . . , $r_N(t)$ **1705** in response. One signal $r_i(t)$ corresponding to each emitter wavelength **1622**. These demodulated signals are plethysmographs, as described above.

The demodulator **1700** has mixers **1730** and low pass filters **1740** for each channel and demodulating signals $d_i(t)$ **1704** provided to each mixer **1730**. The demodulating signals are linear combinations of (orthogonal) basis functions of the form

$$d_i(t) = \sum_{j=1}^{M} \beta_{ij} \cdot \phi_j(t) \qquad \text{(EQ. 5)}$$

which are derived by approximating the optical response of the emitters to on/off periods of the emitter drivers. M is the number of basis functions needed to approximate such optical responses. $\phi_j(t)$ is the j^{th} basis function used by the demodulator. In one embodiment, the basis functions are of the form

$$\phi_j(t) = \sin\left(\frac{2\pi}{T} jt + b_j \frac{\pi}{2}\right); b_j \in [0, 1] \qquad \text{(EQ. 6)}$$

where T is the period of the repeating on/off patterns of the emitter drivers. Accordingly, the lowpass filter outputs **1705** are $r_1(t)$, $r_2(t)$, . . . , $r_N(t)$, which are estimates of absorption for each emitter wavelength in view of noise n(t) that is additive to each channel. Plethysmograph demodulators are described in U.S. Pat. No. 5,919,134 titled Method and Apparatus for Demodulating Signals in a Pulse Oximetry System, issued Jul. 6, 1999; U.S. Pat. No. 7,003,338 titled Method and Apparatus for Reducing Coupling Between Signals, issued Feb. 21, 2006; and U.S. patent application Ser. No. 13/037,321 titled Plethysmograph Filter, filed Feb. 28, 2011; all assigned to Masimo Corporation and incorporated by reference herein.

Advantageously, a plethysmographic respiration processor **100** (FIG. **1**) is implemented on an advanced pulse oximetry monitor or an advanced blood parameter monitor,

as described above. Although a plethysmographic respiration processor is described above with respect to deriving respiration rate from a plethysmograph waveform, in other embodiments, a plethysmographic respiration processor may be used to derive other respiration-related parameters. In a particularly advantageous embodiment, a plethysmographic respiration processor is used in conjunction with an acoustic monitor or combined blood parameter and acoustic monitor so as to improve the accuracy of, robustness of, or otherwise supplement acoustic-derived respiration rate measurements or other acoustic-derived respiration parameters.

A plethysmographic respiration processor has been disclosed in detail in connection with various embodiments. These embodiments are disclosed by way of examples only and are not to limit the scope of the claims herein. One of ordinary skill in art will appreciate many variations and modifications.

What is claimed is:

1. A patient monitor configured to determine a respiration rate from a plethysmograph waveform, the patient monitor comprising:

a preprocessor configured to receive a plethysmograph waveform from a noninvasive sensor monitoring a patient and identify a plurality of portions of the plethysmograph waveform which include physiologically acceptable series of plethysmograph waveform pulses; and

one or more processors configured to:

derive a first set of frequencies from a first respiratory-induced modulation in a portion of the plurality of portions,

derive a second set of frequencies from a second respiratory-induced modulation in the portion, the second respiratory-induced modulation being different from the first respiratory-induced modulation,

compare the first set of frequencies and the second set of frequencies to determine whether any of the first set of frequencies matches any of the second set of frequencies within a tolerance,

generate and output a respiration rate in real time to a display from determining that one of the first set of frequencies matches one of the second set of frequencies within the tolerance, and

activate an alarm in real time if the respiration rate satisfies an alarm threshold.

2. The patient monitor of claim **1**, wherein the one or more processors is configured to compare the first set of frequencies and the second set of frequencies until at least determining that none of at least two of the first set of frequencies match none of at least two of the second set of frequencies within the tolerance.

3. The patient monitor of claim **1**, wherein the one or more processors is configured to compare the first set of frequencies and the second set of frequencies by comparing individual frequencies of the first set of frequencies and individual frequencies of the second set of frequencies in an order that depends on a pulse rate for the patient.

4. The patient monitor of claim **1**, wherein the one or more processors is configured to:

derive a third set of frequencies from a third respiratory-induced modulation in the portion, the third respiratory-induced modulation being different from the first respiratory-induced modulation and the second respiratory-induced modulation;

compare the first set of frequencies, the second set of frequencies, and the third set of frequencies to determine whether any of the first set of frequencies matches any of the second set of frequencies and any of the third set of frequencies within the tolerance; and

generate and output the respiration rate in real time to the display from determining that the one of the first set of frequencies matches the one of the second set of frequencies and one of the third set of frequencies within the tolerance.

5. The patient monitor of claim **1**, wherein the portion comprises plethysmograph data captured from monitoring the patient over a period less than 120 seconds.

6. The patient monitor of claim **1**, wherein the one or more processors is configured to:

derive a third set of frequencies from the first respiratory-induced modulation in another portion of the plurality of portions;

derive a fourth set of frequencies from the second respiratory-induced modulation in the another portion;

compare the third set of frequencies and the fourth set of frequencies to determine whether any of the third set of frequencies matches any of the fourth set of frequencies within the tolerance;

generate another respiration rate from determining that one of the third set of frequencies matches one of the fourth set of frequencies within the tolerance; and

derive a combined respiration rate from the respiratory rate and the another respiratory rate.

7. The patient monitor of claim **6**, wherein the one or more processors is configured to:

derive a fifth set of frequencies from the first respiratory-induced modulation in yet another portion of the plurality of portions;

derive a sixth set of frequencies from the second respiratory-induced modulation in the yet another portion;

compare the fifth set of frequencies and the sixth set of frequencies to determine whether any of the fifth set of frequencies matches any of the sixth set of frequencies within the tolerance;

generate yet another respiration rate from determining that one of the fifth set of frequencies matches one of the sixth set of frequencies within the tolerance;

determine that the yet another respiration rate differs from the combined respiration rate by more than an amount; and

reject the yet another respiration rate in response to determining that the yet another respiration rate differs from the combined respiration rate by more than the amount.

8. The patient monitor of claim **6**, wherein the portion comprises plethysmograph data captured from monitoring the patient over a different period than the another portion.

9. The patient monitor of claim **1**, wherein the one or more processors is configured to generate and output the respiration rate in real time to the display from determining that the one of the first set of frequencies matches the one of the second set of frequencies within the tolerance and from determining that an additional condition is met.

10. The patient monitor of claim **9**, wherein the additional condition is met when the respiration rate differs from a value by less than an amount.

11. The patient monitor of claim **1**, wherein the first respiratory-induced modulation comprises a respiratory-induced baseline shift of the portion, and the second respiratory-induced modulation comprises a respiratory-induced amplitude modulation of the portion.

12. The patient monitor of claim **1**, wherein the first respiratory-induced modulation comprises a respiratory-induced baseline shift of the portion, and the second respira-

tory-induced modulation comprises a respiratory-induced shape modulation of the portion.

13. The patient monitor of claim **1**, wherein the first respiratory-induced modulation comprises a respiratory-induced amplitude modulation of the portion, and the second respiratory-induced modulation comprises a respiratory-induced shape modulation of the portion.

14. The patient monitor of claim **1**, further comprising the display configured to present the respiration rate.

15. The patient monitor of claim **1**, wherein the respiration rate comprises the one of the first set of frequencies.

16. The patient monitor of claim **1**, further comprising the noninvasive sensor.

* * * * *